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НАУЧНО-ТЕХНИЧЕСКИЙ ЖУРНАЛ

# ГЕОРЕСУРСЫ

Главное в номере:



2016. Т. 18. № 3
Ч. 1

# GEORESURSY

GEORESOURCES. SCIENTIFIC AND TECHNICAL JOURNAL

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# Ways to Improve the Efficiency of Horizontal Wells for the Development of Oil and Gas Field

*R.Kh. Muslimov*
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**Abstract**. The effectiveness of horizontal wells is tested mainly for increase of oil withdrawal in comparison with usual vertical wells and more rarely for increase of oil recovery factor. In spite of long time application of horizontal wells in Tatarstan Republic, Russia, its efficiency is comparatively low: flow rates of horizontal wells are in 1,5-2,2 times hither than flow rates of vertical wells. The article deals with geological conditions for the effective application of horizontal wells and their limitation for the development of oil and gas fields. Particular attention is paid to the state analysis and the efficiency improvement of horizontal wells operation during field development with introduction of various water flooding systems. The highest technical and economic indicators of field development with horizontal wells are obtained by their systematic use taking into account the experience of developing oil fields with vertical wells, compliance with principles accumulated for decades of the rational field development by means of flooding.

**Keywords**: horizontal, multi-branched, vertical wells, geological, commercial, initial recoverable reserves, production rates, cumulative production, oil recovery factor

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In the last quarter of the last century, the drilling of horizontal wells in the world has developed at an unprecedented pace. Later, this boom came in the Russian Federation. There were different kinds and constructions of horizontal, multi-branched, branched-horizontal, and, later, lateral branches in the previously drilled (old) wells. Efficiency of horizontal wells is assessed mainly by increase in the current oil production compared with conventional vertical wells and less increase in oil recovery factor. Spread in values of flow rates of horizontal wells compared to flow rates of vertical wells in the whole world is very high, from 5.2 up to 10 and even (in some cases) to 20 times.

This spread (especially in the high values more than 3-5 times) is mainly due to the variety of geological conditions in the application of horizontal drilling. The more challenging the conditions of application of horizontal drilling, the relative increase in oil production by horizontal well will be higher than by vertical well, until the lack of alternatives for the application of horizontal wells. The latter include deposits with the oil rim of small thickness between the gas cap at the top, underlying by an active aquifer. An example is the Troll field in the North Sea. Also deposits of heavy, high-viscosity, extra-viscous oil are included, as well as deposits in tight reservoirs (not previously considered in the state balance). Oil production in said geological conditions using vertical wells is generally unprofitable. In some cases, without horizontal drilling it is not possible to develop (drilling under the settlements, protected, inaccessible areas, water bodies).

The Republic of Tatarstan in the last quarter of a century has gained a lot of experience. As of 01.01.2011 in the Republic of Tatarstan 531 horizontal and 82 branched horizontal wells (Khakimzyanov et al., 2011).

In PJSC «Tatneft» are in operation 464 horizontal wells, including 79 branched-horizontal wells were drilled. Cumulative oil production is 7119 thousand tons, including by horizontal wells – 6901 thousand tons, by branched-horizontal wells – 1028 thousand tons, including production from carbonate reservoirs – 4580 thousand tons, from clastic reservoirs – 2538 thousand tones. On average, one drilled well produces 13.1 thousand tons of oil, including from the carbonate reservoirs – 11.3 thousand tons, from clastic – 18.7 thousand tons. Average oil production rate is 7.9 tons/day; for carbonate and clastic reservoirs – 6.1 and 10.5 tons/day, respectively.

Despite the long period of horizontal wells use in Tatarstan, their efficiency is relatively low: flow rates of horizontal wells in the 1.5-2.2 times higher than rates of vertical wells. There are a number of objective reasons:

1. The heterogeneity of the object, which determines the efficiency of the development as a whole; for the horizontal drilling it is significantly higher. High heterogeneity leads to low coverage of oil displacement (in percentage to the penetrated length of the reservoir) and acceleration of the watering process in operation of horizontal wells without special equipment that separates intervals with different permeability.

2. The deterioration of the filtration properties of the reservoir due to prolonged exposure to drilling muds, as well as during longer operation of horizontal wells than vertical wells.

3. Changes in the stress state of rocks in the horizontal well have a more significant impact on the change in reservoir properties than in the vertical well.

4. Development of deposit by horizontal well with flooding of directed filtration flows that provide necessary formation energy and higher sweep by flooding require a more serious approach. In this case, the injection wells also have to be horizontal (Zakirov et al., 2009).

5. In the application of horizontal wells it is necessary to solve a number of issues of technical and technological nature (length optimization of the horizontal portion, the definition of necessary entry point into the reservoir, the profile and position of horizontal well in deposit, disconnection for separate

| | | Valu | | Difference |
|---|---|---|---|---|
| | | Horizontal wells | Vertical wells | |
| 1 | Revenues, thous.rub | 325698 | 266811 | 58887 |
| 2 | Oil and gas production tax, thous.rub | 105283 | 86248 | 19035 |
| 3 | Business expenses, thous.rub | 16669 | 13655 | 3014 |
| 4 | Variable costs, thous.rub | 8159 | 6684 | 1475 |
| 5 | Prime cost of commercial output, thous.rub | 236063 | 163459 | 72604 |
| 6 | Sales profit, thous.rub | 89635 | 103352 | -13717 |
| 7 | Profit tax, thous.rub | 21512 | 24804 | -3292 |
| 8 | Profit remained in organization, thous.rub | 68123 | 78548 | -10425 |
| 9 | Net Present Value (NPV) | -27073 | 58882 | -85955 |
| 10 | Profitability index | 0,95 | 2,04 | -1,09 |
| 11 | Payback period, years | 1,05 | 0,49 | 0,56 |

*Table 1. Economic indicators for the plot No.7.*

operation of sites with different geological characteristics).

All this calls for a more accurate study of geological features of the object, especially in inter-well space.

Analysis of technical and economic efficiency of drilling horizontal wells in 7 plots in the second block of Kizelian deposit, Bavlinsky field, conducted by G.F. Yulmetova, showed:

1. Lack of technological effect from horizontal drilling in the development in natural mode (2 plots).

2. In areas with flooding technological indicators of horizontal wells (oil flow rates, productivity) are better than for vertical wells, but not much (1.1 to 1.5 times).

Economic indicators in comparison with vertical drilling with distance 400 m between wells (drilling of two vertical wells instead of one horizontal with horizontal branch of 400 m long, recognized the optimal in Tatarstan) are significantly worse (Table 1).

Based on the above, for the correct determination of the economic efficiency of development using horizontal wells, it is necessary to compare it with the system of vertical wells, given that horizontal drilling reduce the vertical drilling by 1-2 wells and so on.

Accumulated horizontal drilling experience suggests that in most cases, to improve efficiency of horizontal drilling, it is necessary to create a development system using horizontal wells, and not be limited by drilling the single horizontal well or multi-branched wells. In this case, we obtain a synergistic effect from horizontal drilling. However, in most cases, in the design and implementation of horizontal drilling, a non-systemic approach is marked.

The fact is that the horizontal wells and branched-horizontal wells in platform deposits with their low energy do not solve the issues of improving the efficiency of development of reserves. They are the only elements of the development system, organically fit into this system. As in the development systems using vertical wells it is necessary to comply with the balance of injection and sampling, to optimize density of well grid and the selection and discharge pressures, to provide control and regulation of the development process, and adjust the direction and shape of fluid flow in the reservoir.

The horizontal drilling has developed at the Fedorovsk oil and gas field, the largest in Western Siberia, in order to engage oil and gas difficult to recover from the formations AS4-8, the feature of which is the presence of bottom water and gas cap, and a small thickness (8-12 m) of oil rim (Fig. 1) (Muslimov, 2005).

Given the encouraging results of the first horizontal wells and the low efficiency of the vertical wells (low flow rates and high

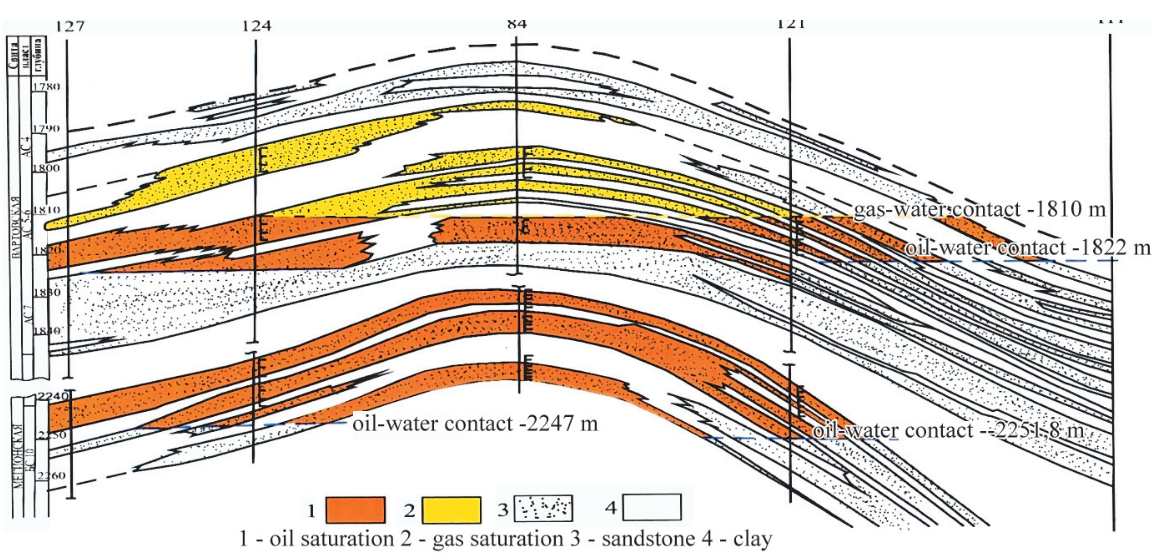


*Fig. 1. Geological profile of productive deposits for the formation AS4-8 of the Fedorovsk oil and gas field.*

water cut), in 1994 the Tyumen branch of SurgutNIPIneft compiled the development plan of oil and gas formation AS4-8 of the Fedorovsk field using horizontal wells.

Technological scheme provided drilling of 1931 wells, including 1175 producing wells, of which 1003 horizontal wells and 756 injection wells. Drilling of this amount of horizontal wells has no analogues in the world (Fig. 2).

Then, in the process of designing the project fund has been increased to 2511 wells, of which 1003 horizontal wells.

The horizontal drilling out provides the involvement in the development of 522.4 million tons of oil, or 86.8% of the approved reserves, additional 100.8 million tons of oil (16.8% of proved reserves). According to hydrodynamic calculations the oil recovery factor doubles. This came from the fact that the depression using the horizontal drilling is much lower compared to the vertical drilling. The quantities of impermeable layers at the gas-oil contact and water-oil contact hindering gas flow and bottom water at the well bottom are reduced, respectively, to 2 m and 1 m.

For project horizontal wells the average length of the horizontal portion of 550 m was adopted. This value is substantiated by detailed technical and economic calculations, but the authors highlight that the actual length of the horizontal part should be justified for each horizontal well under the terms of its construction. The main provisions, which guided the authors of the project document, are that the drilling of each individual horizontal well should be conducted on individual technological scheme, in which it is necessary to determine the specific geological structure of the formation along the path of horizontal well.

The technological scheme provides construction of 60-65 wells per year. Project profiles of horizontal wells are the most widely used, consisting of portions: vertical, drift angle with large and medium curvature radius and horizontal. The average displacement to the entry point into the formation is 550 m, with a spatial azimuthal curvature 65-70°.

On Fedorovsk field OJSC Surgutneftegas solved the main technical and technological issues of deposits development by horizontal wells system: construction, drilling of horizontal wells (direction of trunk and entry into formation, the profile and provision of the specified interval of horizontal portion), wellhead and downhole equipment, optimal length, horizontal section, horizontal portion, distance of the horizontal portion from the gas-oil contact and water-oil contact and others. All of these issues ultimately found their satisfactory solution.

| | Horizontal well | Vertical well |
|---|---|---|
| Number of wells | 215 | 93 |
| Time in operation on 1 well, well – year | 1,5 | 4,2 |
| Cumulative oil production on 1 well, th. t | 14,9 | 16,0 |
| Average oil flow rate, t/day | 29,8 | 10,8 |
| Average liquid flow rate, t/day | 103,0 | 94,0 |
| Cumulative water-oil ratio, t/t | 2,45 | 6,97 |
| Productivity factor, 10 t/day, mPa | 11,0 | 5,5 |
| Measured depth, m | 2800 | 2150 |
| Horizontal length, m | 521 | ––– |

*Table 2. The so-called benefits of the new scheme on reserves approval.*

At the peak of annual output reached by half of the project fund, 28.7% of initially recoverable reserves were extracted (the extraction pace of 3.7% from the initially recoverable reserves) with a very high water content, about 85%.

Effectiveness analysis of the oil rim development in the formation AS4-8 held recently by Yu.N. Avramenko.

On the East-Mokhovaya area, where the experiment began for the development of deposit of horizontal well on an annual maximum (the extraction pace of 6.05 from the initially recoverable reserves), in the extraction of 32.5% of initially recoverable reserves water content was 80.7%.

Analyzing the results it can be concluded that in almost all geological conditions displacement characteristics for horizontal wells are better than for vertical wells, the oil production rate is higher, water and breakthrough gas is produced less. An exception is the oil contacted with gas, where in horizontal wells in the initial stage of operation, the gas factor was higher than in vertical wells.

When comparing the development characteristics with horizontal and vertical wells in the East-Mokhovaya area, it can be seen that at the initial stage of development, characteristics of the displacement in the area with horizontal wells are more favorable. The stabilization of water cut started earlier. If for the plot with vertical wells water cut stabilized at 85%, then for plot with horizontal well it was at the level of 70%, that is, the share of oil in the produced fluid at the same oil recovery factor was 2 times more.

At the same degree of injection (the ratio of accumulated liquid production in situ to balance oil reserves) the current oil recovery factor is higher, the accumulated oil-water factor and gas-oil factor are lower.

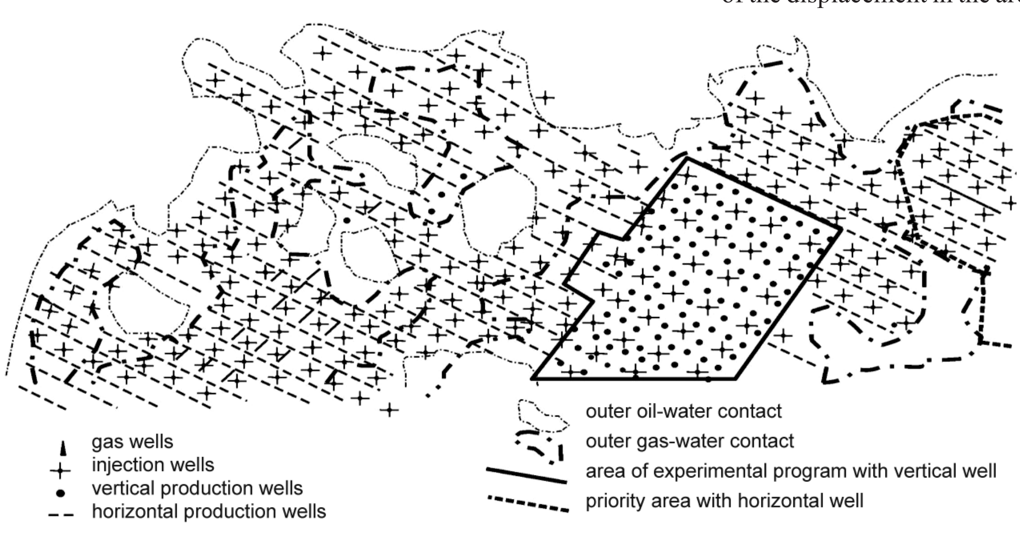


*Fig. 2. Fedorovsk field. Placement of horizontal wells for the formation AS4-8 (fragment).*

Comparison of operation parameters for horizontal and vertical wells is shown in Table 2.

Comparison of operation parameters shows that almost the same oil production (13.9 thousand tons for 1 horizontal well and 16.0 thousand tons for 1 vertical well) was received for 1.5 years of work of horizontal well and 4.2 years of vertical well work. In horizontal well the water was extracted 2.8 times less than in the vertical well (horizontal well – 2.4 tons of water per 1 ton of oil, vertical well -7.0 tons of water per 1 ton of oil).

Extraction of breakthrough gas from the gas cap for the horizontal well is grater than for the vertical well (horizontal well- 982 m3 per ton of oil, vertical well – 862 $m^3$ per ton of oil).

Average production rates for the period of operation are as follows: oil – horizontal well – 27.8 tons/day, vertical well – 10.8 tons/day (for horizontal well 2.5 times more), liquid – horizontal well – 103.0 tons/day, vertical well – 94.0 tons/day (1.1 times greater for horizontal well), productivity index is 2 times greater for horizontal well than for vertical well.

Actual indicators of reserves development in 2012 for horizontal well are the best for horizontal well: 59.7% of the initially recoverable reserves were extracted for horizontal wells, 9.2% – for vertical wells. Peak production for 231 horizontal wells in 4.22 times higher than vertical wells, the average production rate is of 22.7 tons/day. For 119 vertical wells the average production rate is of 10.4 tons/day (Fig. 3).

According to calculations in the deposit operation to limit water cut is of 98%, water content in accordance with the implemented system of CIN may reach 0.27 at the design 0.31. Pilot area indicators developed by vertical wells are much worse. With cumulative production of 56.8% from initially recoverable reserves, the water cut was 92.7%, the current oil recovery factor – 0.142, with production rate of oil – 7.4 tons/day. Obviously a project oil recovery factor 0.25 here will not be achieved.

To achieve the project oil recovery factor, and possibly exceed it at the present stage of development of East-Mokhovy depression it is necessary to perform the following activities: change of the development system, creating a block layout, allowing the best use of cyclic waterflooding, change in the direction of filtration fluid flow, in its classic versions to collect oil in the circuit areas followed by their long working off to the water content of 98-99 %. At the same time within blocks injection wells should be transferred to production wells with drilling of old wells. The same measures should be taken

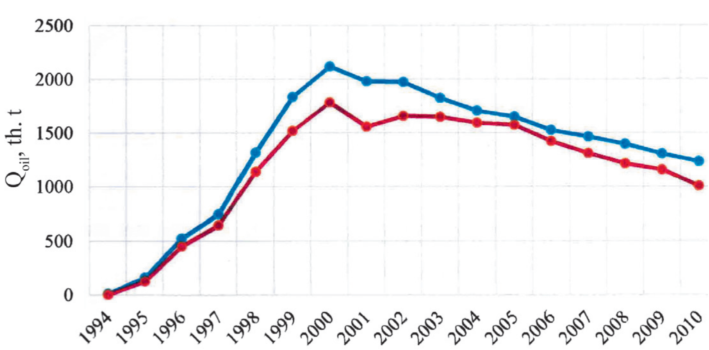


*Fig. 3. The dynamics of oil production indicators in the north of East-Mokhovy area of the Fedorovsk field. – Oil production, total, thousand tons. – including horizontal wells, thousand tons.*

evidently in Fedorovsk field as a whole. This is the experience of the Republic of Tatarstan for the basic technology of circle waterflooding.

Experience of the Fedorovsk field shows that in the most complicated geological conditions of oil and gas object AS4-8 (small oil rim, which lies between the gas cap and underlying water, unfavorable ratio of oil viscosity to water viscosity – 13.6, high heterogeneity and segmentation of layers), the use of traditional systems of development with vertical wells can not provide sufficient current production levels and more or less acceptable oil recovery. The use of horizontal wells significantly increases the current production and ultimate recovery.

However, in the application of horizontal drilling we should take into account the basic principles of development, proven for years of using conventional vertical drilling. This applies to in-depth study of detailed geological structure, allocation of production facilities, assessing the impact of well spacing on the current production and oil recovery, setting operation mode (optimum and minimum allowable values of formation and bottomhole pressures), control and regulation of development processes. We have to pay much more attention to these issues when using the horizontal drilling than in the operation of vertical wells (especially in the study of geological structure, wells operating modes, control and regulation of development processes).

The need for systematic approach to the development of fields with reserves difficult to recover is demonstrated on the experience in developing Kizelsky deposit of Bavlinsky field.

The main feature of deposits in Upper Tournaisian substage is their exceptional heterogeneity and low productivity. For this reason, held for nearly 30 years trial operation and pilot water injection at sufficiently large distances between production and injection wells have not yielded positive results. Therefore, due to unprofitability the reserves of these deposits were transferred to the category of off-balance.

In 1962 TatNIPIneft made a development technological plan of the Lower Carboniferous deposits as a whole, in accordance with which the joint development was performed of Bobrikovian and Tournaisian deposits. However, the practice of joint development of oil deposits, confined to various reservoirs did not pay off; therefore in the project of 1987 carbonate deposits of Tournasian tier were allocated to independent object.

By decision of the Central Committee for Development on priority development areas of Kizelian horizon, experimental work was conducted on the effect of well spacing on the development effectiveness of complex reservoirs saturated with highly viscous oil, as well as the testing of stimulation systems.

In the course of experimental work on one of the sites it was established that the use of cavern storages, organization of flooding, injection of hydrochloric acid provided increased oil recovery by 15-20 % (absolute). The results of the flooding carbonate reservoirs with porosity of 8-11 % at a different site with the development of injection wells were quite encouraging. The expected recovery factor on a site was 0.30 at the design value of 0.2. Drilling and development of one of the sites showed that the mesh density of 4 hectares/well provided enough high rate of annual extraction even in a natural mode.

According to the latest Project Document of 1994 the following was adopted:

- For Kizelian horizon drilling of the combined horizontal wells (8-9 wells per year) and vertical wells with the organization of three-row flooding system, the creation in vertical wells of artificial cavern oil storage, testing of new development technology of carbonate reservoirs with injecting surface-active agents and polymer dispersed systems in the order of pilot development;

- Carrying out on all objects of development of non-stationary flooding.

Investigation of the geological structure of the carbonate productive horizon and generalization of the results of pilot development has allowed identifying the main ways to improve the development of low permeable heterogeneous reservoirs to ensure their cost-effective development.

The object is Kizelovsky deposit of Bavlinsky field, the development of part of which provides essentially horizontal wells.

The total thickness of the development object in the deposit is 21.4 m, for blocks the average values vary from 20.6 to 23.3 m. The total net pay thickness, respectively, equals to 18.6 m changing average values for blocks ranging from 16.0 m to 20.5 m. The average net pay thickness varies according to areas from 5.3 to 8.5 m and average for the deposit is 7.0 m. The proportion of reservoirs in the context of an object changes in the range of 0.268 to 0.435 unit share and averaged 0.369 unit share. The stratification of the section is low and does not exceed an average of 1.548 unit share, while in some wells according to the logging data up to 8 layers of productive reservoirs are allocated. The thickness of dense carbonate layers between reservoirs ranges from 0.4 m to 15.2 m and an average of 5.5 m (Fig. 4) (Khisamov et al., 2013).

On the deposit substantially vertical-lateral development system is applied (Zakirov et al., 2009).

Block 6 is the most drilled both with vertical and horizontal wells on Kizelian object, which accounts for 53% of horizontal wells drilled on the deposit (Fig. 5).

Oil deposit of Korobkovsky area is of massive type. Kizelian horizon of Tournaisian tier consists of limestone. Development of this area of Bavlinsky field was started in 1976.

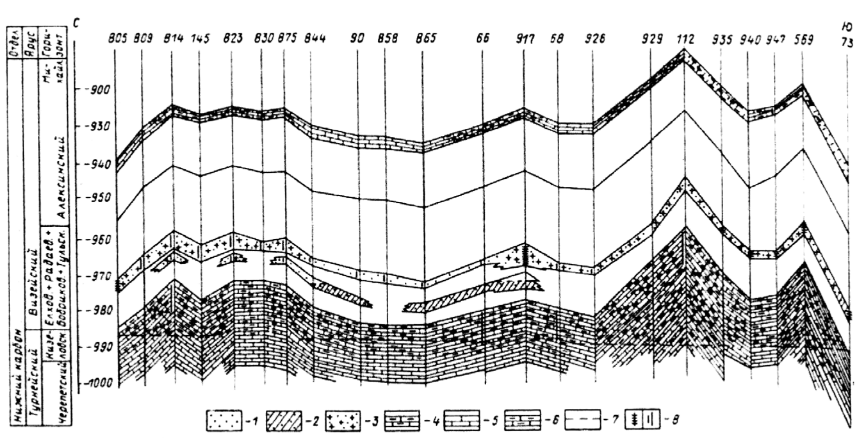

Fig. 4. Geological field profile by line of well 805-73 on the Lower Carboniferous sediments of Bavlinsky field. Clastic rocks, reservoirs: 1 – oil saturated; 2 – water saturated; 3 – water flooded. Carbonate rocks. Reservoirs: 4 – oil saturated; 5 – water saturated; 6 – tight rocks; 7 – oil-water contact; 8 – perforation intervals of injection/production wells.

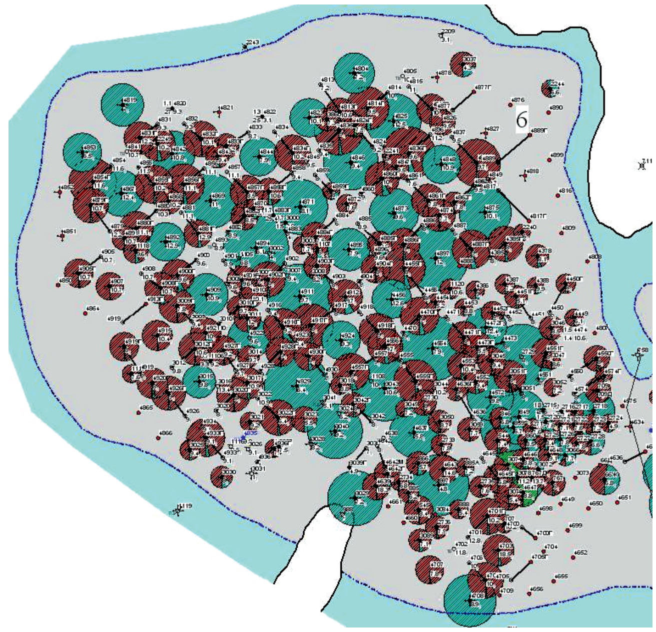

*Fig. 5. Development map of block 6 (Korobkovsky portion) (Podavalov et al., 2016).*

The total thickness of Kizelian horizon averages of 21.4 m, the effective average net pay thickness of 5.8 m; stratification rate is 1.4 unit share. Oil is characterized by medium viscosity 20.8 mPa*s, density – 872.5 kg/m$^3$ at reservoir conditions, the saturation pressure – 3.3 MPa. According to the content of sulfur oil is sour.

In 2002 the Institute TatNIPIneft in collaboration with specialists from geological survey of oil and gas production department "Bavly-Neft" proposed a new complex technology of carbonate reservoirs development (Khisamov et al, 2013; Podavalov et al, 2016.).

The technology includes areal nine-point system of wells with horizontal and system vertical trunks and injection wells in the center of the element. The distance from the injection to the horizontal production well is 450 meters; to vertical corner production well is 635 m (Fig. 5).

In the injection wells it is recommended to conduct vertical seismic profiling for fracture studies. Closure pressure of cracks is determined. Estimates are produced of the required volume of water injection from the conservation of initial reservoir pressure after the selection of the reservoir fluid. The injection wells are perforated in the bottom part of the formation. Anticipatory cyclic water injection is produced, thus preparing the formation for oil extraction. Water injection as displacing agent must be alternated.

After specification of the geological structure of drillable object, vertical and horizontal wells are drilled equidistant from injection wells. The horizontal shaft, as well as the perforations in producing wells is carried out in the top part of the productive formation. This ensures a uniform coverage of the reservoir with filtration flow from the bottom up.

Extraction of well production as water injection is carried out in a cyclic mode.

| Values | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Oil flow rate (vertical well) t/day | 2,3 | 2,1 | 2,3 | 3,2 | 3,4 | 3,7 | 3,9 | 3,7 | 3,4 | 3,8 | 3,4 |
| Oil flow rate (horizontal well) t/day | 6,7 | 3,8 | 5,9 | 6,8 | 8,3 | 8,4 | 8,1 | 7,7 | 7,3 | 7,0 | 6,8 |
| Water flooding (vertical well), % | 14,2 | 19,1 | 17,7 | 14,9 | 10,2 | 9,5 | 10,4 | 12,5 | 15,4 | 16,3 | 17,1 |
| Water flooding (horizontal well), % | 6,0 | 6,5 | 7,9 | 5,3 | 6,7 | 4,2 | 4,6 | 6,7 | 7,6 | 6,3 | 3,9 |
| Producing well fund (horizontal wells) | 1 | 4 | 9 | 15 | 24 | 27 | 36 | 46 | 57 | 65 | 73 |
| Producing well fund (vertical wells) | 46 | 51 | 61 | 73 | 76 | 76 | 77 | 85 | 94 | 102 | 105 |
| $P_{deposit}$, mPA | 7,6 | 7,4 | 7,5 | 7,9 | 8,1 | 7,8 | 8,04 | 7,1 | 6,8 | 7,5 | 7,4 |

*Table 3. The dynamics of flow rates, water content and the existing fund of vertical and horizontal wells.*

Since 2002, the drilling and operation of Korobkovsky area is carried out by adopted technology (Podavalov et al., 2016).

As of 01.01.2016, there are 172 producing (71 – horizontal) and 40 injection (1 – horizontal) wells are in the industrial exploitation, of which 8 are in the permanent work from the group pumping station (KNS-12), the remaining injection wells operate from the wells giving process water in a cyclic mode.

In 2015, oil production on the object in question was 293.6 thousand tons, the rate of extraction from the initial recoverable reserves – 6.9%, 343.6 thousand tons of the liquid was produced with water cut of 14.6%. In order to maintain reservoir pressure 72 thousand m3 of water was pumped.

The dynamics of flow rates, water content and the existing fund of vertical and horizontal wells is shown in Table 3 and Figure 6. The oil flow rate and water cut of the sun and the HS are shown in Figure 7 (Podavalov et al., 2016).

It draws attention to the discrepancy between the oil extraction rate and water cut of production. At the very high depletion of deposits (76.6% of the initially recovered reserves) water content is only 14.6%, which is contrary to the development experience (especially for oils with a higher viscosity (Fig. 8) (Muslimov, 2014). With such low water content the current oil recovery factor is 0.153 at the design 0.2. At the same time the pace of development is very high – 6.9% annually from initially recoverable reserves (compared to conventional deposits in carbonate formations of Tatarstan 0.5-1, at least 2% per year). Moreover, such oil recovery was achieved at an early stage of development when the reservoir did not even reached the maximum annual production.

What's the matter? Such indicators may be either due to underestimation of balance reserves, or by understating the project oil recovery factor when applied new technology of development, or by both. Obviously on the considered deposits we are dealing with the third case. With regard to the under-balance reserves we are dealing with carbonate array, in which the current practice of determining the so-called balance reserves is not perfect. They are defined only by artificially allocated, so-called permeable interlayers. Calculated on the accepted technique share of reservoirs in this case is about 45%. But in the development the whole carbonate array participates. With this in mind, reserves are understated by half.

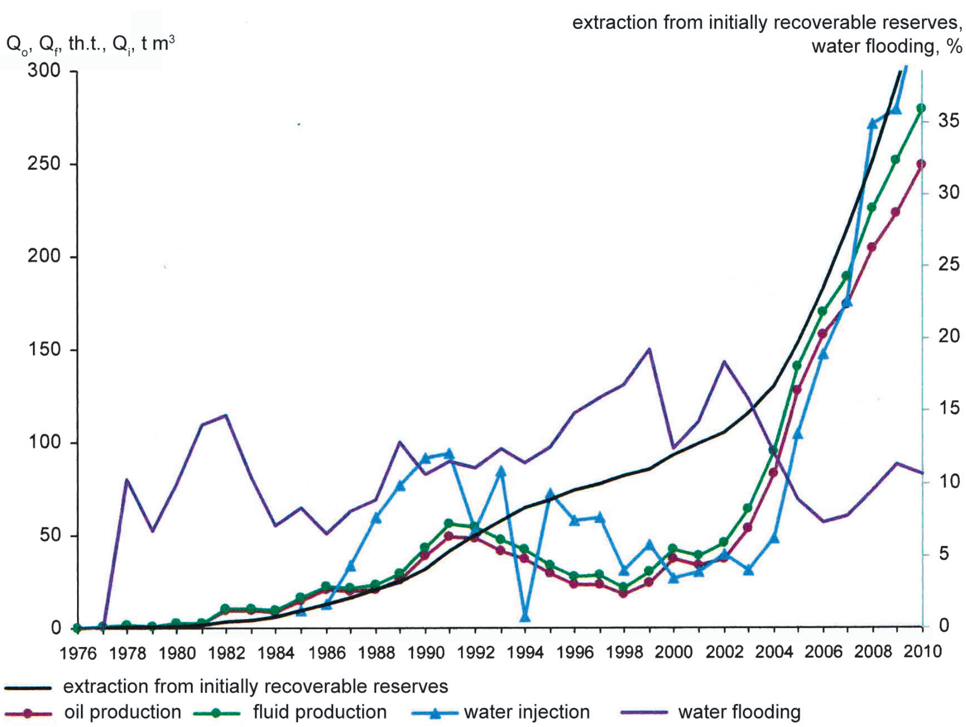


*Fig. 6. Development scheme of the Kizelian horizon*

Recent studies of the Kazan Federal University (V.P. Morozov et al.) for the Upper Tournasian deposits of the east board of Melekess depression showed the presence of oil in almost all oil-saturated part of the section.

According to many modern concepts about the oil and gas basins (Morariu, Averyanova, 2013; Prischepa, Averyanova, 2013), the following rock types can be distinguished in them:

- Reservoir rocks (conventional);
- Source rocks (unconventional);
- Dense rock or half-reservoirs.

If the conventional reservoirs are usually localized within anticline structures, the unconventional reservoir rocks do not comply with it. Important features of oil and gas deposits in shale reservoirs and tight reservoirs that distinguish

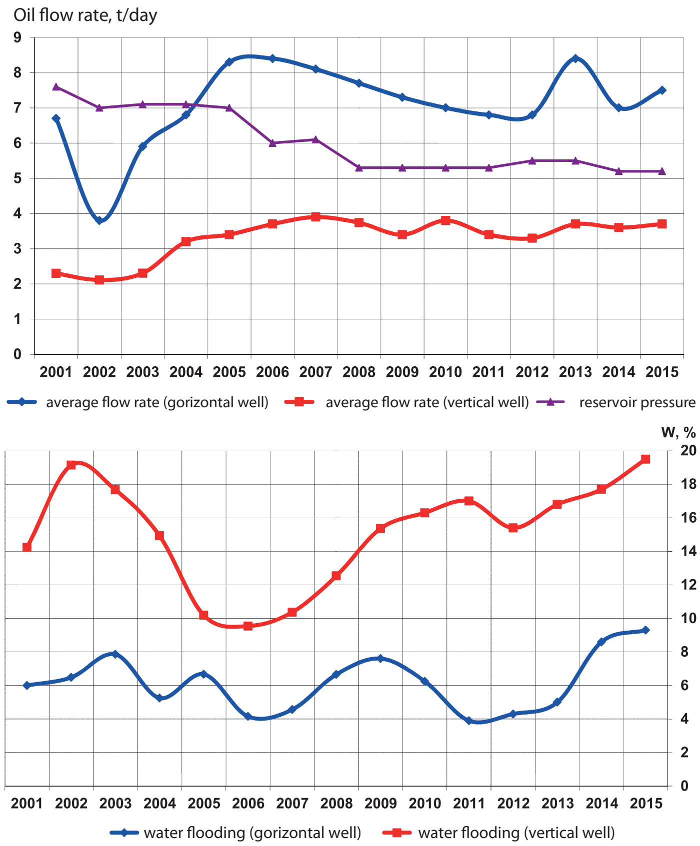


*Fig. 7. Distribution of flow rates and water cut of horizontal and vertical wells of block 6 (Podavalov et al., 2016).*

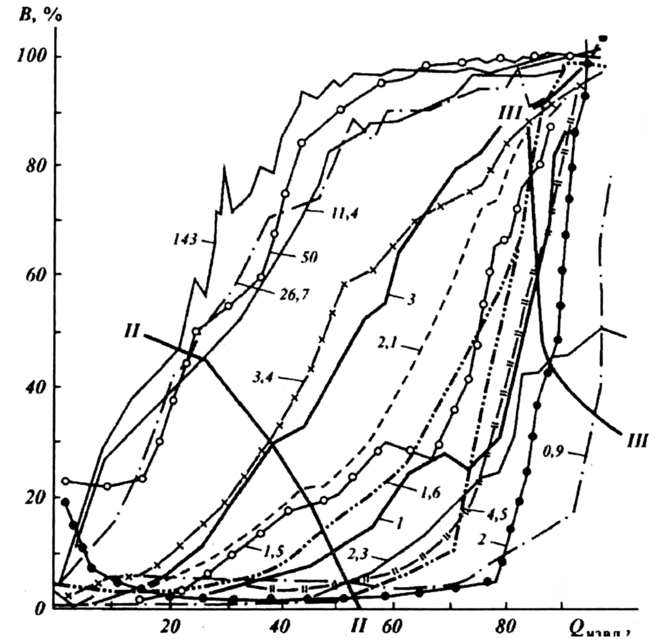


*Fig. 8. Dynamics of product water cut in the development of production facilities with varying viscosity of reservoir fluid (M.M. Ivanova et al.).*

them from conventional deposits, are:

- Continuous type reservoir;
- Are not controlled by the structure factor;
- Controlled by stratigraphic and lithological factors.

Therefore, the prevalence of non-conventional reservoir rocks, controlled by lithological and stratigraphic factor has a very wide areal distribution.

The result of work held by V.P. Morozov et al was the presence among the studied sections of tight oil-saturated carbonate rocks with potential industrial oil bearing.

Thus, the study of core material sections of the Lower and Middle Carboniferous show that it is possible to distinguish carbonate rocks by the degree of oil saturation:

- Oil-bearing rocks;
- Tight with no signs of oil;
- Tight oil-bearing rocks, intermediate between them (half-reservoirs).

V.P. Morozov on an area of 8.5 thousand km$^2$ on the eastern board of Melekess depression defined in the tight layers 8.5 billion tons of oil. Thus, the geological reserves in carbonate array are substantially above the so-called balance reserves. According to our research, the so-called tight sections in carbonate and clastic reservoirs take an active part in the processes of filtration and oil displacement (Muslimov, 2014). Therefore, some experts strongly suggest to go on account of the so-called balance reserves to geological reserves (Zakirov et al, 2009; Muslimov, 2005; 2014). Then discrepancy will disappears between the large selections from the recorded reserves on the balance sheet and low water cut on Korobkovsky area. A similar pattern is observed throughout the Republic of Tatarstan.

The second aspect relates to the effectiveness of development technology in the area with the use of horizontal drilling. The calculations of oil production until the end of the development, to the water content of 98% showed the possibility of achieving oil recovery factor 0.369, i.e. initially recoverable reserves will be more on the balance sheet by 1.84 times. Given the necessary adjustment of reserves (switching to geological), this value of initially recoverable reserves should be increased at least twice.

But this does not exhaust the possible effectiveness of this technology. It can be improved and further developed.

The real basis of the adopted technology is the application of horizontal wells and vertical lateral cyclical flooding. As substantiated in the publications of S.N. Zakirov (Zakirov, Zakirov, 1996) it is proved that if horizontal production well is drilled, it must be complemented by a horizontal injection well. In addition, over time, the selection of 80% or more from the actual oil reserves, which are described above, it is necessary to use such a powerful lever as a change in the direction of filtration of liquid flows in the formation, changing the location of production and injection wells, transferring on the block developing system that allows to concentrate residual oil in particular, already emerged areas and ensuring that it is selected with the use of classical schemes of non-stationary flooding. At this we estimated that oil recovery factor would amount to 0.45 to now adopted balance reserves (or 0.361 to adjusted geological reserves). The latter requires a special calculation for the methods recommended by specialists of the Kazan Federal University.

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# Production of Hard-to-recover and Non-recoverable Oil Reserves by means of Binary Mixtures Technology

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**Abstract**. The paper discusses the results of the enhanced oil recovery by means of binary mixtures containing mineral (ammonium) and/or organic (mono-ethanolamine) nitrate and initiators of their decomposition. Calculations and large-scale field experiment show that resource-saving technology of binary mixtures can be considered as an alternative to the well-known thermal steam technology (Canada, USA). Designed and tested by the authors monitoring system of temperature and pressure in the reaction zone of the well, which provides conversion depth and efficiency coefficient of binary mixtures reaction that are close to 1 is a necessary and sufficient condition for the successful application of this method for the purpose of enhanced oil recovery.

**Keywords**: heat of formation, ammonium nitrate, organic nitrate – mono-ethanolamine, binary mixtures, oil production technology, reaction control mode at the bottomhole, thermochemical gas lift.

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## Introduction

At the initial stage of hydrocarbon deposits exploitation, oil is generally extracted using high pressure in the formation that exceeds the bottomhole pressure of production wells. Oil production during the development falls in synchronization with the lowering of the reservoir pressure. In order to maintain production rate for increasing reservoir pressure through injection wells water is pumped into the formation under pressure. Now in Russia from wells, on average, about 90% of water and 10% of oil is extracted (Aleksandrov, Kuznetsov, 2007). In the depths about 60% of proven, but 'non-recoverable' oil remains. Mass of non-recoverable oil is more than mass of oil extracted from the subsoil throughout its production history.

In recent years, there has been a decision to extract non-recoverable reserves using thermochemical technology of binary mixtures. Binary mixture is an aqueous solution of ammonium nitrate (ammonium or organic) and their decomposition reaction initiators (metal hydrides or sodium nitrite) (Aleksandrov, Koller, 2008; Merzhanov et al., 2010). Aqueous solutions of binary mixtures reactants are pumped into the well through different channels. They come into contact in the bottomhole formation zone and react, generating heat and gas that go into a pressurized reservoir, created by the reaction.

## History

Before 2011, injection of binary mixture solutions in wells was produced in unmanaged mode, and Rostekhnadzor allowed using small doses of binary mixtures. Typically, it was not permitted to inject into the well more than one ton of explosive nitrate. In the reaction about a ton of hot gas was produced, which was affecting formation near the well and ensured growth of recoverable oil, usually sufficient to payback the operation (Aleksandrov, Kuznetsov, 2007; Aleksandrov, Koller, 2008; Merzhanov et al, 2010;. Aleksandrov, et al, 2012; 2013).

When implementing the project, International Science and Technology Center No.985 of the Institute of Biochemical Physics of the Russian Academy of Sciences conducted R&D activities in the laboratory and on the field (Chernogolovka, Moscow region). Operating formulations have been developed on the basis of ammonium and organic nitrate (mono-ethanolamine nitrate) and conducted their tests on well No. 21 of Razumovsk field, Saratov region (Aleksandrov, Kuznetsov, 2007). These formulations were then successfully applied in the fields of the Perm region and the Komi Republic (Usinsk deposit) (Aleksandrov et al 2012;. Aleksandrov, Kuznetsov, 2007; Merzhanov et al, 2010; Aleksandrov, Koller, 2008).

The amount of heat introduced into the reservoir by the technology of binary mixture for injection into the well of one ton nitrate, is three times less than the amount of heat introduced into the formation in the next cycle of steam injection according to Canadian steam technology. Therefore, the technology of binary mixtures (TBM) of 2001 (ISTC project No. 985) did not seem able to compete with leading thermal technology of the World SAGD (Merzhanov et al., 2010).

In 2010 the Institute of Biochemical Physics of RAS has developed and tested a system of continuous monitoring and optimization of BM reaction in the wells, and obtained the permit of Rostekhnadzor authorities No. 25-ID-19542-2010 to pump into the subsoil of nitrate without limiting its mass. In the oil fields 2-level explosion-proof system was used of decomposition of tens of tons of ammonium nitrate, injected into the well (Aleksandrov et al. 2012).

System of nitrate controlled injection and initiator of its decomposition into the well can be regarded as a thermochemical gas generator (TG), with which the whole nitrate injected into the formation is converted into gas and heat by the reaction: $NH_4NO_3 \rightarrow N_2 + 2H_2O + 0{,}5O_2 + Qr$. The reaction heats the formation and creates conditions for the gas lift, which works mainly due to the energy of oil oxidation with oxygen, precipitated in the reaction of nitrate decomposition. Live crude after the pressure rise and opening of valves at the wellhead usually gushes.

TG is a new engine of borehole type – in situ combustion engine of oil. TG, as experience has shown, can provide pumping out of hot fluid from the wellbore at a temperature much higher than the limit for operation of commercial motor pumps.

In November 2011, the pilot tests were performed of the technology of binary mixtures (managed by E.N. Aleksandrov). In the wells No.1242 and 3003 of Usinsk field (LLC LUKOIL-Komi) an aqueous solution was injected containing 20 tons of ammonium nitrate, and 9 tons of sodium nitrite.

In 2012 the yield of these wells increased by an average of 4.95 and 8.44 t/d, respectively (Table 1). Weight of additional oil in 2012 amounted to 3400 tons, an average of 1.7 thousand tons per well. At the end of 2011 – beginning of 2012 on the Usinsk field using the BM technology the following wells were treated: 6010,600,1283,7169,8198 (managed by E.N. Aleksandrov, V.B. Zavolzhsky). In 2012, 13232 tons of additional oil was obtained using the BM, on average 2646 tons per well (Table 2).

Therefore:

- The system of regulated non-hazardous injection on seven wells of Usinsk field was created and tested in 2011-2012.

- It has been shown that the system is functioning effectively both technically and economically, providing a ratio of income/expenses not lower than 5;

- Advertising the features of the binary mixtures technology on the Internet led to negotiations with foreign companies and to the proposal from the company ViscosEnergy Ltd. to hold pilot testing in the United States.

## Technology of binary mixtures in the development and competition with the world's leading technologies

In June 2013 products of the binary mixtures reaction treated unprofitable wells No. 8 and No. 10 on the Eastland field, Texas, United States (managed by E.N. Aleksandrov) (Aleksandrov et al., 2012). The field was abandoned by oilfield workers in 1994 as a fully worked out. Prior to treatment from wells No. 8 and No.10 during the week (June 1-8, 2013) formation fluid was pumped out, consisting of water (99.99%) with a film of oil (0.01%). Prior to injection of reagents, the static level of surface water in the well No. 8 was detected at a depth of 210 m.

In the evening, the 9th of June 2013 in wells No. 8 and No. 10 55 tons of aqueous solutions of ammonium nitrate and sodium nitrite was injected into wells No. 8 and No. 10.

| Well No. | Pump brand | Month | Operational date | Base flow rate | Number of days | Average flow rate, t/d | Incremental oil production, t | Specific flow rate, t/d | Planned specific flow rate |
|---|---|---|---|---|---|---|---|---|---|
| 1242 | EVNT-25-1500 | November 2011<br>December 2011<br>January 2012<br>February 2012<br>March 2012 | 09.11.2011 | 0 | 22.00<br>30.83<br>31.00<br>29.00<br>31.00 | 5.82<br>5.50<br>4.63<br>4.94<br>3.98 | 128.00<br>169.57<br>143.00<br>143.26<br>123.38 | | 1 |
| | | **Total** | | | **143.83** | | **707.73** | **4.92** | **8.5** |
| 3003 | EVNT-<br>25-1500 | January 2012<br>February 2012<br>March 2012 | 04.01.2012 | 1.93 t/d | 28.00<br>23.00<br>30.75 | 10.6<br>10.60<br>9.98 | 242.90<br>199.60<br>247.60 | | |
| | | **Total** | | | **81.75** | | **690.10** | **8.44** | **6.5** |

*Table 1. The results of pilot tests of the BM technology in wells No. 1242 and No. 3003 of Usinsk field in November 2011,*

Effectiveness analysis of experimental program Ltd. «NTRS-Komi» on Permo-Carboniferous deposit of Usinsky filed, 2012

| Technology | Well No. | Production facility | Date of procedure conducting | | Well input date after experimental program | Mode of working before procedure | | | Mode of working after procedure | | | Current mode of working | | | Costs, thous. rub | | Increment $Q_o$, t/day | After-production, thous.t | Active days after procedure | Brief characterization of experimental program results | Comment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Beginning | End | | Qж, т/сут | Qн, т/сут | % | Qж, т/сут | Qн, т/сут | % | Qж, т/сут | Qн, т/сут | % | Plan | Fact | | | | | |
| Injection of silicon inorganic compounds | 6010 | P-C | 15.05.2012 | 16.05.2012 | 27.05.2012 | 22,9 | 3,6 | 84,4 | 20 | 6,8 | 67 | 17,5 | 12 | 33 | 780 | 780 | 10,2 | 5,566 | 547 | effective | |
| | 600 | P-C | 03.05.2012 | 04.05.2012 | 12.05.2012 | - | - | - | 21 | 5,9 | 70 | 21 | 5 | 76 | 780 | 780 | 5,0 | 1,05 | 81 | effective | non-operating well |
| | 1283 | P-C | 12.05.2012 | 15.05.2012 | 17.05.2012 | 9 | 4,5 | 50 | 25 | 13 | 46 | 22 | 13 | 42 | 780 | 780 | 9,6 | 2,16 | 225 | effective | |
| | 7169 | P-C | 12.12.2012 | 12.12.2012 | 14.01.2012 | 49,4 | 5,6 | 88,6 | 62 | 15 | 76 | 21,7 | 1,3 | 94 | 780 | 780 | 8,4 | 1,644 | 194,9 | effective | effect till August, 2013 |
| | 8198 | P-C | 25.12.2011 | 04.01.2012 | 10.02.2012 | 49,2 | 0,8 | 98,3 | 41 | 13 | 68 | 22,6 | 6,1 | 73 | 780 | 780 | 9,1 | 2,812 | 307,7 | effective | |
| Total | | | | | | | | | | | | | | | | | 9,8 | 13,232 | 1356 | | |

*Table 2. The treatment results of five wells on the Usinsk field in late 2011 - early 2012 (Managed by E.N. Aleksandrov, V.B. Zavolzhsky).*

According to the work plan, half of the reagents reacted in the well by providing approximately 25 tons of gas heated, an average of 300 ° C, which went to an adjacent layer under the pressure generated by reaction. The other half of the BM, stopping the reaction in the well was injected into the heated reservoir. In the reservoir slow decomposition reaction of nitrate continued for more than 3 days (Fig. 1, graph of pressure change in the well No. 8 for 09-12 June 2013, Table 3). The pressure at the wellhead No. 8 increased to 15 atmospheres. Given that the liquid level in the well increased to 210 meters due to the pressure increase by 21 atm, the total pressure increase due to the decomposition reaction of ammonium nitrate, mainly in the formation was 36 atmospheres.

After the cessation of pressure rise at the wellheap, valves were opened. Figure 2 shows a picture of the gush from well No. 8. The well No. 8 selected in the center of the field gave fluid with composition: oil – about 30%, water – about 70%. Well No. 10 chosen on the edge of the field gave fluid with composition: oil – 10% water – 90%.

The contracting company in the United States ViscosEnergy Ltd. placed an online advertising with the heading "Comparison of technologies" about the successful revival of oil production in the abandoned Eastland field using the revolutionary technology of binary mixtures. In the ad it was written: "Scientists based in Russia have developed and tested a technology of output stimulation by heat from reactions of binary mixtures (BM)".

ViscosEnergy Ltd. presented the stimulation results by BM reaction products, oil production from wells No. 8 and No.10 for the Eastland field (Texas, USA) (Table 3). These results are compared in the advertisement with the results of stimulation by leading technologies of the West: fracturing technology (hydraulic fracturing, the United States) and thermal steam technology (SAGD, Canada).

The second row of Table 3 shows that the BM technology as opposed to Western technologies, waters the subsoil much less (i.e. negligible). The third row of the table specifies the potential of technologies for their ability to maximize the beneficial share of proven reserves:

- SAGD 30%;
- hydrofractures 35%;
- BM is not less than 50%.

The eighth row of Table 3 contains the cost of a barrel of oil extracted from the subsoil: SAGD (50-60) &/BBL; hydraulic fracturing (40-60) &/BBL; BM (10-35) &/BBL. The BM technology, which value is determined by market competition, until 2012, held the third place in the world and was inferior to hydraulic fracturing technology (US) and thermal steam SAGD technology (Canada). In 2012-2014 BM technology, ensuring oil production by cost (10-35) &/BBL, is ahead in terms of profitability of both leading Western technologies.

It should be emphasized that the published in the advertising cost of oil barrel, extracted from the subsoil by the existing profitable fields using SAGD – (50-60) &/BBL and hydraulic fracturing – (40-60) &/BBL is compared with the cost of oil (10-35) &/BBL, extracted from the subsoil by means of BM in unprofitable field left without the protection 19 years ago. Modern technology of BM, being developed by the authors from 1997 is different from other technologies by optimized heat generation during injection, which ensures high efficiency of the reaction close to 1. With the BM technology

| **Criteria** | **SAGD** | **Hydrofractures** | **Binary mixture** |
|---|---|---|---|
| **Principle** | **Heats the formation with steam to lower viscosity** | **Pacal's Law: Cold liquids requiring strong pumps fracture formation** | **Heats the formation to lower oil viscosity. Uses reactions to increase energy and gas lifting** |
| **Damage to well** | **Rapid water-logging** | **Rapid water-logging** | **No irrigation or any other damage** |
| **Production over time** | **non-economical after appx. 30% of oil is extracted** | **non-economical after appx. 35% of oil is extracted** | **Can extract 50-80% of all oil from the well over its lifetime** |
| **Energy loss** | **+/- 25% to heat water and to transfer it to well** | **strong pumps (>10.000 HP), proppants** | **Negligible loss** |
| **Depth limits** | **800-1000m (more, if costly thermo-insulated tubing is used)** | **Depends on well construction and strength of pumps available** | **Unclear; deepest wells at 15,000 ft** |
| **Temperature reached** | **250°C** | **N/A** | **From 100-500°C, fully regulated** |
| **Investment** | **Large upfront investment** | **Moderate** | **Moderate** |
| **Production costs** | **$50-60/BBL** | **$40-60/BBL** | **$10-35/BBL depending on geological/market conditions** |
| **Environment-friendliness** | **Water pollution and exhaust gases in athmosphere** | **High water consumption** | **Limited; by-products are nitrogen, water, and C02. All other solid materials (if indeed any) remain down in the well.** |
| **Repeatability** | **Increasing water content lowers economical effect** | **Repeated stimulation has lesser effect** | **Can be repeated many times or can run permanently** |

*Table 3. The treatment results of wells No. 8 and No. 10 on the Eastland field, USA (managed by E.N. Aleksandrov).*

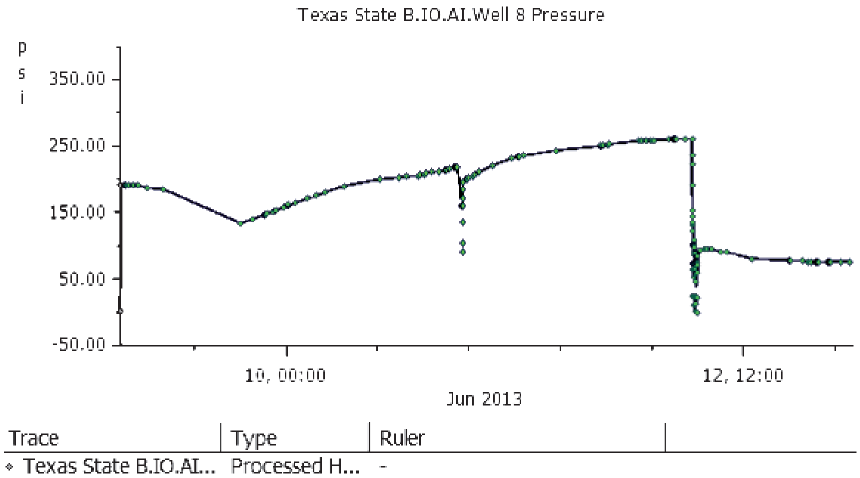


*Fig. 1. Graph of pressure change in well No. 8 during June 9-12, 2013, with the valve closed at the wellhead during 3 days with the fourth day after injection of BM into the well and formation.*

*Fig. 2. Picture of mixture gush (water – 70%, oil – 30%) from the well No.8.*

we managed to find the real possibility of complete removal of the skin layer around tens of thousands of currently uneconomic wells in Russia, which has accumulated over several decades of their not resource-saving operation. This layer seems to be the main cause of the 'shortage' from of 60% proven oil reserves in Russia. The skin layer is comprised of heavy viscous oil particles that are more sorbed by pore and crack walls than light oil. Cooling fluid contributes to the sorption greatly during its exit from the formation into the borehole (Joule-Thomson effect).

## Binary mixtures technology perspectives

From a number of perspective 'branches' of TBM we will consider, for example, the possibility of using the binary mixtures in the wells of the Canadian tandem (Fig. 3). Steam replacement in wells tandem to the BM solutions is planned to make in the following manner.

BM solutions must be pumped into the lower horizontal shaft, wherein it is easy to organize the continuous reaction of BM fed into the well via the installation of low-power pumps CA-320. Capacity of BM reaction, generating hot gas in the well at a temperature of about 300 °C, must exceed the capacity of hydraulic fracturing pumps (10 thousand liters a second). Thus for a few hours we can arrange a discharge drainage of hot gases from the low horizontal shaft to the upper horizontal shaft of tandem, in which the conditions will be created for continuous operation of thermochemical gas lift. It is capable of continuous delivery of hot fluid to the surface, containing a mixture of oil and water at a temperature close to 100 °C. As a result of replacement of production mode SAGD to the BM mode, we can expect an increase in the speed of heavy viscous oil production by an order of magnitude.

If successful, lowering of SAGD production costs will be ensured by costs reduction to almost zero in the creation of the steam generator plants. (Injection of BM in Russia is usually done with 'wheels' of installations CA-320, applied for cementing, and always available in the fields). Production accelerating is also expected by eliminating the steam injection periods, during which the production in SAGD system is not conducted. Thus the opportunity to use the advantages of steam tandem that is not applied deeper than 1 km due to heat losses steam towards the bottomhole area, also in wells with horizontal shafts at any depth. Considering planned by us continuous process, in which an order of thermochemical gas lift capacity exceeds the capacity of mechanical pumps, we should expect a radical production stimulation of both heavy and light oil.

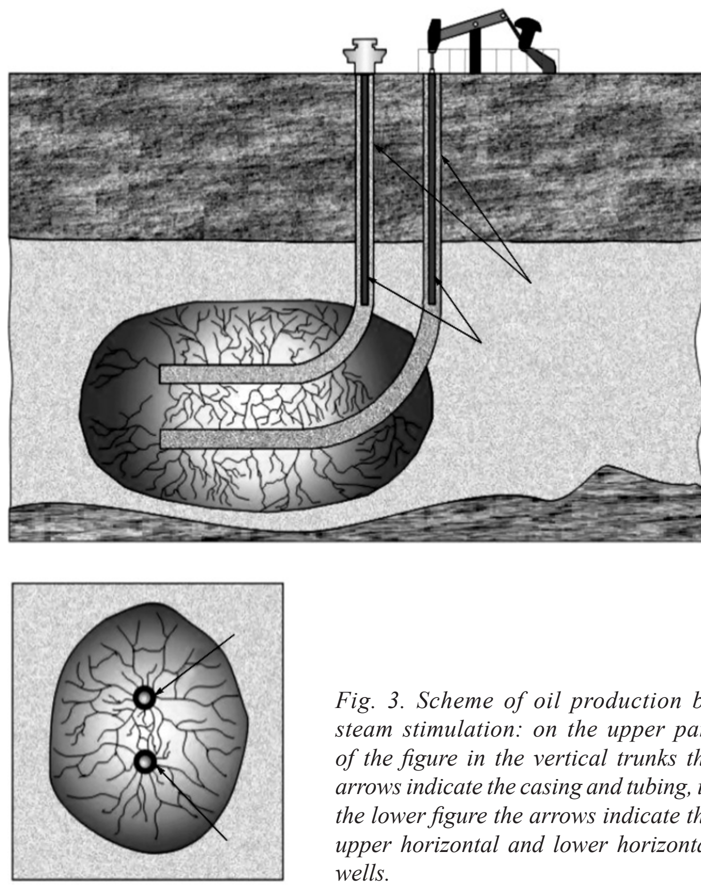

*Fig. 3. Scheme of oil production by steam stimulation: on the upper part of the figure in the vertical trunks the arrows indicate the casing and tubing, in the lower figure the arrows indicate the upper horizontal and lower horizontal wells.*

During the pilot testing on the Usinsk field we discovered previously unknown heat wave of nitrate decomposition in the formation initiated by heat of the heated portion via the BM reaction in the well. The heat wave moved from the well into the formation to almost complete decomposition of nitrate injected into the formation. This wave is displayed in the graph of pressure changes in the well No.8 (Eastland field) during 09-12 June 2013 with the pressure build-up at the beginning of nitrate decomposition reaction at a closed valve in the wellhead (Fig. 1, the pressure drop in the evening of 10 June there due to short-term leaks of wellhead, the cause of which quickly liquidated).

It should be emphasized that due to the complete explosion of heat by expanding any mass of nitrate in the formation, giving the bulk of the heat to formation rocks, the use of this heat wave becomes the main focus of the BM application to a massive stimulation of oil production (Calculation of heat wave movement of nitrate decomposition is shown in the paper (Kuznetsov, 2016)).

## Technology of binary mixtures as an alternative to SAGD technology

We believe that in the future the BM technology should replace the SAGD technology. We believe that (at least initially) in the BM technology we can use well tandem characteristic for SAGD technology.

During the reaction in the formation near well a zone of high pressure is created, in which the gas is produced. Formation fluid movement through the pores and cracks under the ga pressure is called the pressure drainage.

Unlike the gravity drainage of steam technology, pressure drainage, supported by the energy of the BM reaction, is a process controlled by the intensity and direction. In addition to the pressure drainage effect at the BM reaction in the well and formation, the gas evolved in the reaction is soluble in the formation fluid, making it less viscous and lighter. Gas lift is a movement of fluid saturated by gas upward the borehole. Artificial gas lift, supported by the energy of the BM reaction was found in the well No. 169 of Kurbatovsky field (Perm region) (Aleksandrov, Kuznetsov, 2007).

## Conclusion

The recovery of the industrial oil production in the Eastland field (USA) in 2013 by means of BM reaction, which for 1994-2013 was considered unrecoverable, can be regarded as an opportunity to turn from more than a century of accumulation in the depths of non-recoverable oil reserves for their cost-effective production. In the depths there are hydrocarbons, the mass of which at times exceeds the reserves at fields developed currently. Finding the possibility of extracting 'uneconomic' oil reserves is equivalent to the discovery of new major fields with almost no costs for geological prospecting and exploration. This result has no analogues in the prior literature.

As is clear from the eighth row of Table 3, the leading Western technologies SAGD technology and hydrofractures, used now in active, i.e., cost-effective fields in terms of production profitability deposits ceded primacy to the BM technology applied at an abandoned unprofitable field. This result also does not have analogues in the prior literature.

Recovery of oil production with the BM technology on currently uneconomic fields is the new direction of the commercial thermochemistry, which can provide improvement for the economy of Russia as a great energy-producing nation.

## Findings

1. The method of thermo-chemical stimulation of oil production is developed and mastered by means of new technological elements:

- System of adjustable safety heat up of oil reservoirs in the temperature range 200-700 °C;
- Thermochemical gas lift used for pumping out the formation fluid at high temperatures.

2. At identic production modes on Usinsk and Texas fields, technologies tested in the United States have paid off for two months.

3. Revival of oil production in depleted fields should be considered as a promising new direction of commercial thermochemistry.

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# Actual Problems of the Gas Industry at the Current Stage

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**Abstract**. Today, the Russian Federation has a leading position in the world in terms of gas reserves and gas production, is one of the largest suppliers to the world market of energy resources. The authors analyzed the domestic gas industry as a component of the global energy market. Recently there has been increased competition due to the commercial development of new types of energy in the global energy market, which results in the structure change and reduction in exports for the domestic gas industry. However, the share of Russian reserves of hydrocarbons, which are located in remote areas with poor infrastructure, away from the end user, as well as low-rate reserves, increases every year. The solution to these problems is to increase energy efficiency and the production of marketable products, their processing with high added value.

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Russian gas industry is one of the key sectors, on which the proper functioning of the national economy and social sphere depends, and not only national, but to a large extent the world's energy security. The Russian Federation ranked second in the world in natural gas production and first in terms of global gas reserves. It is one of the largest suppliers of energy resources to the world market, occupying a leading position in the world in gas export. Today, Russia exports over 40% of energy resources, accounting for 16% in the structure of the global inter-regional energy trade.

Currently, the share of gas in the fuel balance of Russia is 62%, but if we consider only the European part of Russia, it will reach 86%. Domestic gas industry provides about 10% of the national gross domestic product, up to 25% of revenues to the government budget. The contribution of the foreign exchange component of natural gas exports accounts for about 15% of the total foreign exchange earnings of the Russian Federation (Mirovaya energetika na rubezhe 2015 goda…, 2015).

According to the Ministry of Economic Development regarding the intention of the EU to reduce its dependence on Russian gas imports at the expense of other types of fuel, gas exports to non-CIS countries in 2016 will decrease by 0.8% compared with 2015 to 184 billion cubic meters. Gas exports in 2016 is expected to reach 184 billion cubic meters, in 2017 – 188.7 billion cubic meters, in 2018 – 190 billion cubic meters, in 2019 – 189.4 billion cubic meters. Average contract price for gas to the far abroad in 2016 are planned at the level of 159.2 dollars per 1 thousand cubic meters, in 2017 to 167.2 dollars, in 2018 – 159.1 dollars, in 2019 – 174,8 dollar, and for CIS countries – in 2016 to 152.5 dollars per 1 thousand cubic meters, in 2017 – 160.1 dollars, 2018 – 152.1 dollars, in 2019 – 168.2 dollars.

Thus, in the near future it is expected to reduce revenues from the export of gas to the government treasury. To maintain its leading position on gas export of Russia, it is necessary to study the trends in the global energy market and to find new gas markets and trade its products.

The past 2015 for the global energy economy has been linked not only to the volatility of oil prices, changes in transport infrastructure development plans and the adjustment of trade flow directions. It is also characterized by the continuing depletion of easily accessible deposits of conventional oil and gas, energy shortages in some regions of the world, strengthening of measures to improve the efficiency of natural resources, reduction of anthropogenic load on the environment. In 2015, a number of countries of the Organization for Economic Cooperation and Development (OECD), in particular Japan, South Korea, Germany, Britain, France, Italy and Spain, reached the upper limit of power consumption (Mirovaya energetika na rubezhe 2015 goda…, 2015).

In the past few years, the structure of demand for primary energy (oil, gas, coal, and electricity produced by hydro and nuclear energy stations) has been subjected to minor changes. Figure 1 (Razvitie neftegazovogo kompleksa..., 2014) presents the world's primary energy consumption structure by the end of 2014.

Currently, oil continues to dominate, accounting for about 33% of global primary energy demand and, in spite of the price crisis, the growth rate of production of this raw material is not slowed down. The share of gas is stable – at 24% of total energy consumption, and a similar figure for coal, competitiveness of which increased (due to a lower price per unit of calorific value), exceeded the level of 28%, despite attempts to curb its use for environmental reasons.

One of the consequences of the accident at the "Fukushima-1 nuclear power plant" was to reduce the generation of nuclear power, which share in the expenditure part of the global energy balance has declined from 6% in 2003 to 4.4% in 2013. At the same time, the share of electricity generated by hydropower has gradually increased and reached in 2014 approximately 6.7% of the world total. In 2013-2014, in some countries progress has been notable in the application of renewable energy sources (RES biomass, solar, wind, water, earth, waste energy), but on a global scale, estimated by the corporation British Petroleum, the

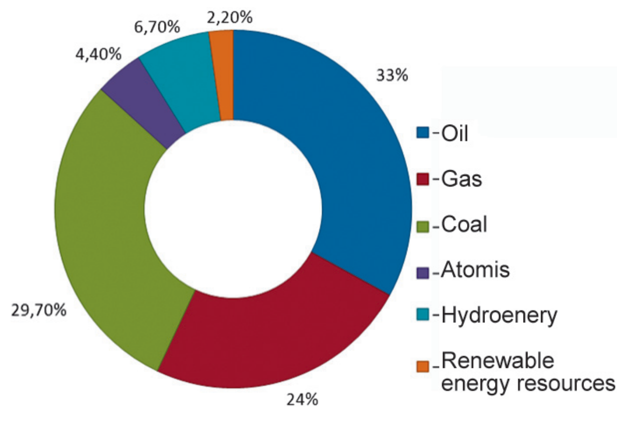


*Fig. 1. The structure of the global primary energy consumption, 2014.*

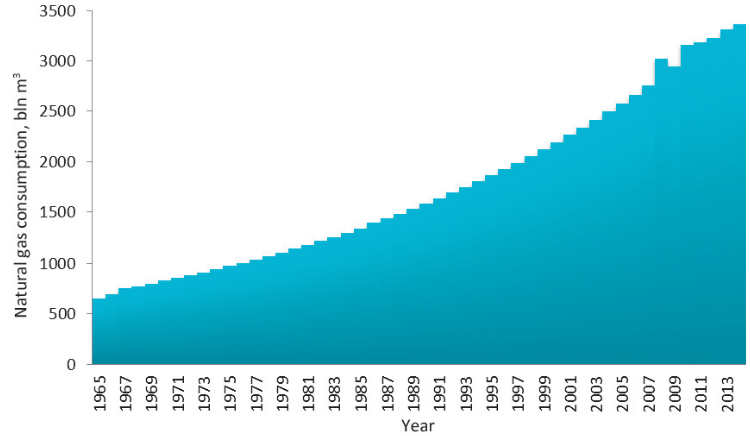


*Fig. 2. Dynamics of natural gas consumption (BP Statistical Review of World Energy, June 2014).*

importance of these energy sources remains low (2.2%) (Mirovaya energetika na rubezhe 2015 goda…, 2015).

In the near future we can expect that the trend of natural gas share of growth will only be strengthened. Experts attribute this fact to several factors, among which are the more favorable environmental properties of the gas compared with oil and coal; the rapid development of gas chemistry, which has long been very much behind the petrochemical industry in terms of growth; a revolution in the field of gas transport, namely the rapid spread of technology of liquefied natural gas (LNG) and its transportation by sea worldwide (Mayorts, Simonov, 2013).

And finally, today power plants are actively being replaced, operating on liquid and solid hydrocarbons to the gas turbine power plant of combined cycle, which are currently the cheapest (in terms of the unit cost of power generation units), efficient and environmentally friendly energy sources.

Along with the growth of energy consumption in the global energy balance the share attributable to natural gas increases.

Figure 2 shows a retrospective dynamics of natural gas consumption. The diagram in Fig. 3 shows that the main consumer of gas is the United States. It is followed with a considerable margin by Russia, China and Iran.

Russia ranked first in the world at the beginning of 2015 for the volume of proved natural gas reserves (50 trillion $m^3$), which corresponds to 26.7% of the world reserves (209.3 trillion $m^3$) (Fig. 4).

It should be noted that in the years 2005-2014 gas reserves have grown in all regions of the world, but mostly in North America, where growth amounted to 58% at the expense of the US and Canada, while reducing gas reserves in Mexico. Multiple increase of gas reserves in Turkmenistan offset their decline in the Netherlands, the United Kingdom and Norway, with the total growth in a decade at 32.5%. For the Pacific region, representing another growing region of gas reserves, this period is associated with an increase in Australia by 54% and 1.5 times in China.

At the end of 2014 global gas reserves have also increased by 0.5%. In addition, by 2015, China for the first time made the list of top 10 countries in terms of

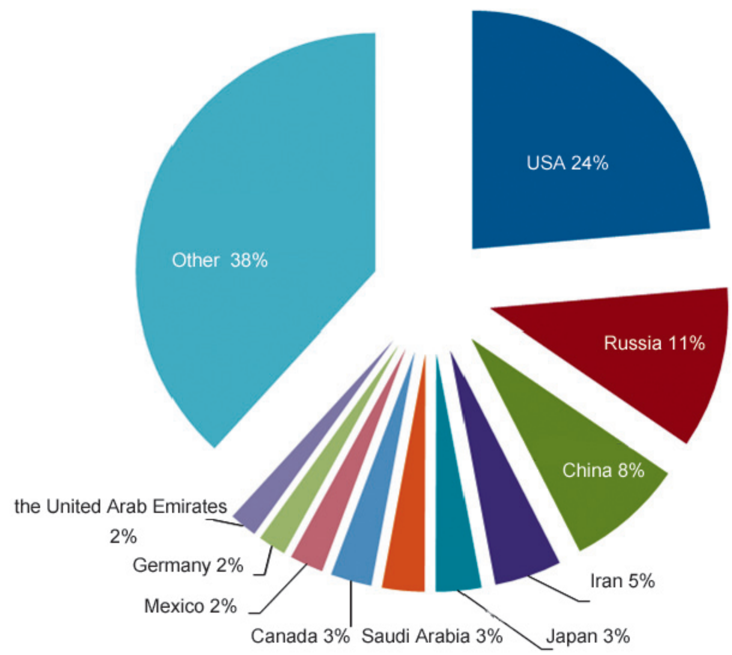


*Fig. 3. Gas consumption by countries, 2014 (BP Statistical Review of World Energy, June 2015).*

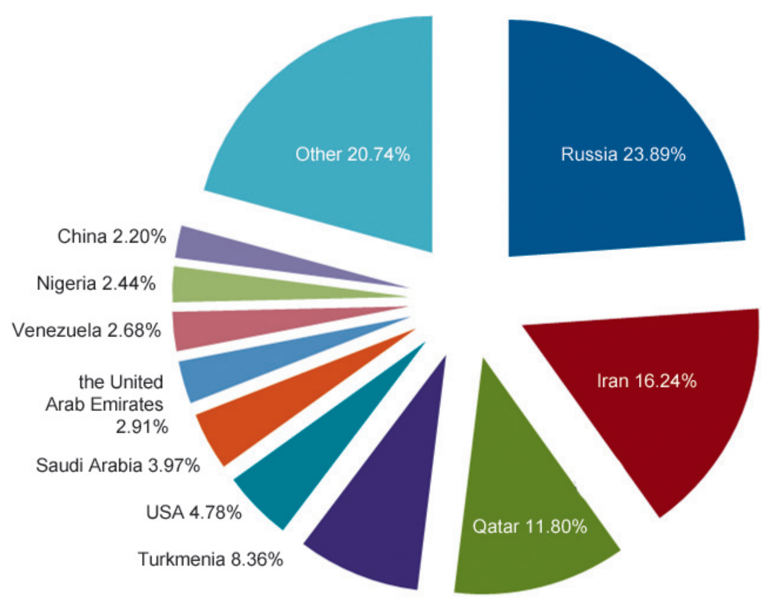


*Fig. 4. The total volume of proved natural gas reserves by countries. (BP Statistical Review of World Energy, June 2015).*

natural gas reserves, replacing Algeria from this position. The discovery of new offshore fields near the coasts of East Africa and the Eastern Mediterranean and their development of a high degree of probability will help to tighten competition in the growing LNG regional markets, both European and Asian.

Fig. 5 shows countries with maximum growth/reduction of gas reserves at the end of 2014 (Mayorts, Simonov, 2013).

Leaders of gas reserves growth in 2014 were the United States, Russia, China and Iran. The maximum reduction is shown for Australia. The share of the top ten countries in the global gas reserves increased during the year to 79.3% (Fig. 6).

Table 1 presents data on the production of natural gas in Russia and in the world in 1970-2014 years. (Razvitie neftegazovogo kompleksa..., 2014; Razmanova et al., 2015.).

Against the background of growing demand for energy in 2010 there was an increase in gas production in the CIS countries, with the result that the share of CIS countries deliveries exceeded 28% of the world supply. At the same time, gas production in Kazakhstan increased from 32 to 37 billion $m^3$, in Azerbaijan from 14.8 to 16 billion $m^3$, in Ukraine from 19 to 21 billion $m^3$, in Turkmenistan from 64.4 to 75.1 billion $m^3$ (Mirovaya energetika na rubezhe 2015 goda..., 2015; Ananenkov, Mastepanov, 2010).

In general, the gas production in the CIS countries amounted to 861 billion $m^3$ in 2010, which is a record in the history of the gas industry in this area. At the beginning of the 1990 gas production in the USSR exceeded 800 billion $m^3$ (Table 1). Then it was more than 40% of world production, while in Russia 641-643 billion $m^3$ of gas was produced per year (more than 32% of the world), though at the expense of fields in Western Siberia – more than 580 billion $m^3$ (Mirovaya energetika na rubezhe 2015 goda..., 2015).

Almost 90% of Russian gas production is concentrated in West Siberia (West-Siberian Federal District), in the first place in Yamalo-Nenets Autonomous Region – in excess of 80% (Fig. 7). The main gas producing regions of the European part, which accounts for about 7% of national production – is the Orenburg region (the Volga-Ural region), Astrakhan Region (Caspian region) and the Republic of Komi (Timan-Pechora region). In recent years, the development began of the Okhotsk province (the continental shelf).

Over the past two decades, there is a reduction of Russia's share in global gas production, indicating the slowdown in the Russian gas industry, due to the active operation of the main gas fields of Western Siberia in the last quarter of the century.

As a result of restrictions of gas supply and increasing demand for it, the economy could face unprecedented challenges. In this regard, the role of unconventional gas reserves increases in order to compensate the decline in conventional gas production and thus ensure the economic security of the country. This is an important area, but in the shortest time it will not be able to fully compensate for a deficiency of the mineral resource base, in connection with what is currently at the stage of formation and pilot development.

Improving the energy efficiency of production and the use and processing of natural gas is the key to economic efficiency and increase of commercially viable oil reserves and improvement of the financial performance of production companies. An example of the successful implementation of energy efficiency programs is OJSC "Gazpromneft", which in recent years managed to reduce

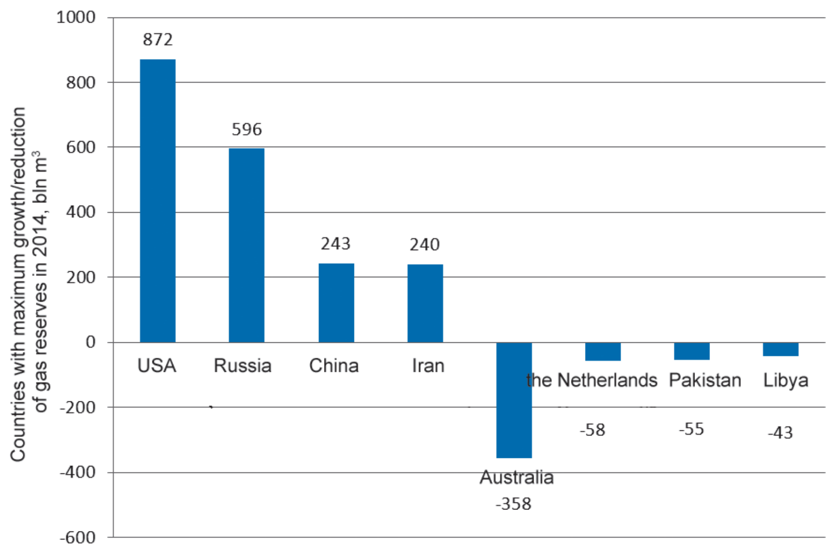


*Fig. 5. Countries with maximum growth/reduction of gas reserves in 2014.*

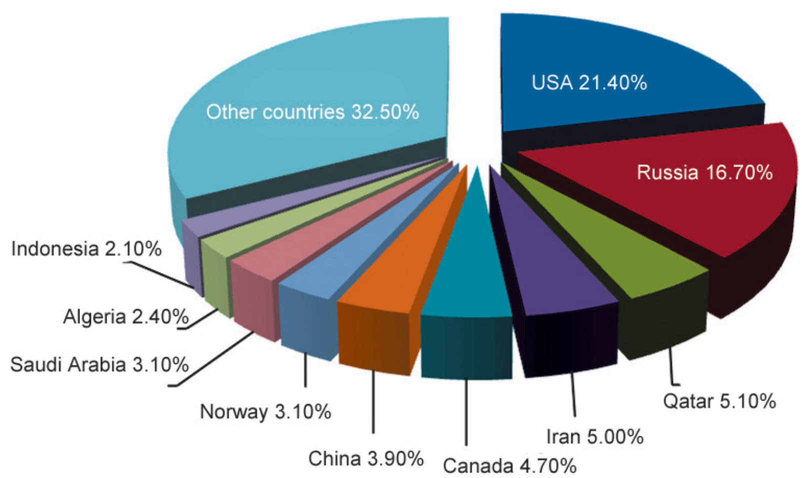


*Fig. 6. The share of 10 largest gas-producing countries in the world production in 2014 (BP Statistical Review of World Energy, June 2015).*

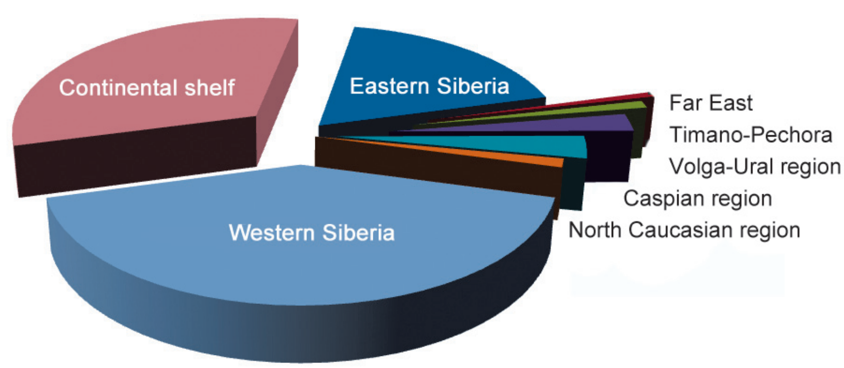


*Fig. 7. Gas reserves distribution of gas producing regions of Russia.*

production energy costs and thus increase the production of gas. (Sokolov, Iskritskaya, 2015).

Despite the fact that the Federal Law No, 261-FZ about the increasing energy efficiency was adopted in 2009, there is still no single methodology of its definition, as in the financial statements there are no indicators that take it into account. The production companies use indicators of energy efficiency, but at the same time, often having similar names, they are different in content. Development and application of methods of financial analysis, taking into account energy efficiency indicators reveals the reserves to reduce operating costs at the enterprises of the fuel and energy complex.

Thus, the example of an integrated energy and financial analysis of OJSC "Yakutsk Fuel and Energy Company" has proved this method and found ways to increase the profits of the enterprise (Steblyanskaya, Feng, 2016).

The basis of increasing the economic efficiency of development of natural gas fields is an integrated approach, when there is the possibility of expanding the range of commercial products, obtained during the extraction and processing of raw materials.

At the moment, the major gas companies consider options to diversify natural gas supplies, access to new gas export markets and opportunities to reduce dependence on market supply pipelines.

Given the fact that Russia has a leading position in the global natural gas market, as well as the unique geographical location, which allows the country to supply gas to all major trading exchanges and major regional markets, gas trade development and production of gas chemical complex is one of the priority export destinations of the Russian Federation.

The Draft of Energy Strategy of Russia for the period up to 2035 "provides for the diversification of energy export trade structure", including due to the increase in its share of LNG. According to the Draft, Russia's share in world LNG trade is expected to increase with the level of 2% (about 11 million tons) to 12% (55.1 million tons) in 2020, and 19.3% (87 million tons) in 2025 (Energeticheskaya strategiya do 2035 goda, 2015).

Currently, more than 65% of Russian gas exports destined for Western and Central Europe, which goes by pipelines through Ukraine and Belarus, and the Baltic Sea. With the transportation infrastructure of natural gas supplies, created in the last quarter of the last century, today, unfortunately, problems are associated such as dependence of Russia on gas transit through the territory of third countries and the lack of geographic diversification of Russian gas supplies. Of course, Russia is interested in ensuring the reliability of gas exports, and is forced to consider other options for transportation of natural gas, including LNG.

Today, supply diversification options include the already constructed gas pipeline "Nord Stream", laid under the Baltic Sea from Russia to Germany, as well as promising pipeline "Power of Siberia", "Nord Stream-2", as well as LNG projects. Transport of LNG by marine gas carriers will also enable Russia to escape from the problems of transit through a third country.

Russia plans to significantly increase capacity for the production of liquefied natural gas and expand its presence in the global LNG market, including in the Asia-Pacific Region (APR). However, competition of LNG suppliers in foreign markets, lower prices for energy, sanctions imposed on Russian companies by Western countries, and a number of other problems complicate the implementation of the task. But, despite all the difficulties, work continues for a variety of project.

As a promising area for processing of natural and associated gas GTL-product is now considered, which means not a synthetic oil as a semi-finished, but an end products of its processing – diesel fuel and motor fuels. Thus in the structure of the final product diesel predominates. The long-term market for the FTGTL products of possible future Russian FTGTL plants, located in Eastern Siberia and the Far East, are the EU countries, South-East Asia and the west coast of North and Latin America.

Petrochemical industry can be confidently called a multiplier of the value. Moving up the supply chain, from raw materials to petrochemical intermediates, petrochemicals, polymers and products made from polymers, in the petrochemical industry the cost is building up to 8-15 times of the original cost of raw materials (Khorokhorin, 2015). Gas chemical industry is part of the petrochemical industry. Its existence is obliged to expand of petrochemical material base, and use of natural

| Year | World, bln $m^3$ | USSR (before 1990), CIS | | the Russian SFSR (before 1990 ), Russia | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | Western Siberia | |
| | | bln $m^3$ | Share of world, % | Total, bln $m^3$ | Share of world, % | bln $m^3$ | Share of Russia,% |
| 1970 | 1021 | 198 | 19,4 | 83 | 8,1 | 3 | 3,2 |
| 1980 | 1456 | 435 | 29,9 | 254 | 17,4 | 140 | 55,3 |
| 1985 | 1676 | 643 | 38,4 | 462 | 27,6 | 389 | 84,2 |
| 1990 | 2000 | 815 | 40,8 | 641 | 32,1 | 574 | 89,6 |
| 1995 | 2141 | 707 | 33 | 595 | 27,8 | 545 | 91,5 |
| 2000 | 2436 | 710 | 29,1 | 584 | 24 | 533 | 91,3 |
| 2001 | 2493 | 712 | 28,6 | 581 | 23,3 | 532 | 91,6 |
| 2002 | 2531 | 728 | 28,8 | 595 | 23,5 | 545 | 91,5 |
| 2003 | 2617 | 761 | 29,1 | 620 | 23,7 | 574 | 92,6 |
| 2004 | 2694 | 784 | 29,1 | 634 | 23,5 | 590 | 93,1 |
| 2005 | 2778 | 799 | 28,8 | 641 | 23,1 | 594 | 92,7 |
| 2006 | 2876 | 820 | 28,5 | 656 | 22,8 | 604 | 92,1 |
| 2007 | 2945 | 833 | 28,3 | 653 | 22,2 | 611 | 93,6 |
| 2008 | 3066 | 857 | 28 | 665 | 21,7 | 610 | 91,7 |
| 2009 | 3045 | 789 | 25,9 | 582 | 19,1 | 517 | 88,7 |
| 2010 | 3060 | 861 | 28,1 | 650 | 21,2 | 575 | 88,5 |
| 2011 | 3115 | 820 | 26 | 685 | 23,6 | 580 | 90 |
| 2012 | 3211 | 870 | 29 | 690 | 24,2 | 590 | 93,6 |
| 2013 | 3316 | 865 | 30 | 700 | 25 | 570 | 91,2 |
| 2014 | 3460 | 880 | 31 | 715 | 26 | 540 | 90 |

*Table 1. Natural gas production in Russia and in the world in 1970 -2014 years.*

gas as direct raw material, as well as processed products of natural and associated petroleum gas (ethane, propane, butanes, fractions of gas condensate) (Arutyunov, 2013; Razmanova, Machula, 2016).

Methanol is one of the product that most important for the gas chemical industry. Over the past few years, many changes have occurred in the methanol industry – production technology significantly improved, new plants for the synthesis of methanol were put into operation; the volume of its consumption rapidly increased and continues to increase.

In coming years, Asian countries, mainly China will be performing as growth driver on the methanol market. If European demand by 2019 is expected to reach 10 million tons, the Chinese will reach 70 million tons. In general, the global consumption of methanol in 2019 will be about 100 million tons (an increase of 47% compared to 2014). According to the expert (Looking to the future, 2015), this jump is due to a change in consumption patterns (mainly in China): the proportion of MTO, formaldehyde and methanol as the fuel itself will increase. Growing demand will be satisfied by new industries. If the integrated MTO projects (mostly Chinese, with aggregate capacity of 12.3 million tons in the period up to 2017) will affect mainly on the olefin segment, the non-integrated market will give the world an additional 4.6 million tons of methanol (Looking to the future, 2015) .

Varied use of methanol in fuel elements, in the pharmacy industry, in the chemical industry for the production of solvents, methylmethacrylate, methylamines, dimethyl terephthalate, methyl formate, methyl chloride, acetic acid resins indicates the need to increase production capacity (Konov, 2009). Given the forecast expansion of its consumption in the EU and the Asia-Pacific region, Russia is advantageous to produce methanol for export, with its production so as the shipping costs would not be significant.

Today, Russia needs to go to the higher added value of product market, since it is obvious that the production and sale of petrochemical products of higher added value in the long run is more cost effective than the production and subsequent sale of hydrocarbons. Analysis of the current status and trends of development of the gas industry indicates that for the solution of the problems standing in the way of its successful development, it is necessary: to react promptly to changes in the global energy market, to compete for new markets for export, to create in the domestic market manufactures of profound processing of gas with its subsequent delivery to the foreign market; to improve energy efficiency of the production processes and gas processing in order to reduce operating costs and increase the profits of enterprises.

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# Tensor Representation of Capillary Model of a Porous Medium (Theory and Experiment)

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**Abstract**. Generalization is given for the case of anisotropic porous media represented by a simple model of capillary porous medium. It is an idealized model in which the porous medium is a periodic lattice formed by mutually perpendicular cylindrical capillaries. It is assumed that each capillary system is characterized by its parameter $d_a$ and stacking period $a_a$ (a = 1, 2, 3). It is shown that for anisotropic porous media, the functions of pore density distribution by radius and the values of the equivalent pore diameter depend on the direction and are set by symmetric tensor of the second rank. Scalar values of equivalent pore diameter are calculated, as is customary in crystal physics, in the form of the tensor properties along a predetermined direction. In the article an idea is given of the permeability coefficients tensor for simple capillary model of porous media and showed that the direction permeability value is determined by the tensor composition of luminal factor and pore distribution density by radii. The proposed theoretical representations of pore distribution density by radii; equivalent pore diameter and permeability coefficients are tested on the experimental data obtained in the laboratory experiment on a real core material. The main directions of the permeability tensor are determined from the extreme values of the transmission velocity of ultrasonic waves through the lateral surface of the core. Measurements on the control sample confirmed the tensor nature of the permeability. Pore distribution curves by radii are obtained by tomographic studies of core samples (device SkyScan 1172). A good agreement between theoretical and experimental results is obtained.

**Keywords**: simple capillary model, anisotropic media, filtration properties, characteristic linear dimensions, luminal tensors, pore distribution density by radii.
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The generalization of classical filtering theory models to the case of anisotropic filtration properties is relevant, since the real hydrocarbon reservoirs are porous and fractured media, almost always have anisotropy. Increasing the information content of the anisotropic core study for oil and gas field is also an important practical problem for determining the structure of pore space, filtration properties of the reservoir and estimation of reserves, as well as for optimum placement of wells and direction of horizontal wells.

1. **A simple capillary model for anisotropic porous media**. For a description of seepage flows in porous media mathematical models are often used, in which the real porous medium is represented in the form of capillary systems, cracks, packages of balls, etc. The most popular models include a simple capillary model of direct parallel capillaries whose radii are distributed according to a F(r) distribution function, so that

$$F(r)=\int_0^r f(r)dr, \tag{1.1}$$

where f(r) is the density distribution of pore radius, f(r)dr – fraction of the pore space with capillaries whose radii lie in the interval from r to r + dr (Dmitriev, 1995; Dmitriev, Maksimov, 2001; Dmitriev et al, 2012. ). In this approach, knowing f(r) we can determine the effective radius and capillary permeability. The effective capillary radius is determined by the formula (Romm, 1985)

$$r_э=\int_0^\infty rf(r)dr, \tag{1.2}$$

to determine the permeability we have the formula

$$k=\frac{m}{8}\int_0^\infty r^2 f(r)dr. \tag{1.3}$$

Equations (1.1) – (1.3) are valid only for the extremely anisotropic media: the model of rigid tubes, which allows for the filtration only along one direction. In this case, the porosity equals to luminal factor (Dmitriev, 1995; Dmitriev, Maksimov, 2001), and the permeability is represented by the equality $k=mr_э^2/8$. If we consider the three-dimensional capillary model of anisotropic porous medium, it is clear that the equality (1.1) – (1.3) can be written for each of the main directions of the tensor permeability coefficients in

$$k_\alpha=\frac{s_\alpha}{8}\int_0^\infty r^2 f_\alpha(r)dr,\ r_i^э=\int_0^\infty rf_i(r)dr,$$

$$F_i(r)=\int_0^r f_i(r)dr,\ \alpha,i=1,2,3 \tag{1.4}$$

where $s_\alpha$ – are principal values of the luminal factors tensor (Dmitriev, Maksimov, 2001), hereinafter by repeated Greek indices summation is not performed; the summation is only over repeated Latin indices.

Introduction along the main lines of luminal si values and density functions of pore distribution by radius $f_i(r)$ in fact means postulating of luminal tensors $s_i$ and distribution density of capillaries radius $f_{ij}(r)$. This approach allows moving from the scalar notation, such as (1.2) and (1.3), to tensor and determining tensor of the effective radii of the capillaries in the form

$$r_{ij}^{э} = \int_0^\infty r f_{ij}(r) dr, \tag{1.5}$$

and for the tensor of permeability coefficients in a simple capillary model we write equation

$$k_{ij} = \frac{1}{8}\int_0^\infty r^2 s_{ik} f_{kj}(r) dr \tag{1.6}$$

As noted above, over repeated Latin indices in (1.6) and so on summation is meant.

Values of the effective pore diameter and the permeability coefficient along an arbitrary direction is defined as the tensor property in a given direction (Dmitriev et al., 2012) by

$$r^{э}(n) = r_{ij}^{э} n_i n_j = \int_0^\infty r f_{ij}(r) n_i n_j dr, \tag{1.7}$$

$$k(n) = k_{ij} n_i n_j = \frac{1}{8}\int_0^\infty r^2 s_{ik} f_{kj}(r) n_i n_j dr, \tag{1.8}$$

respectively. For the main directions the formulas (1.7) and (1.8) give the equation (1.4).

For orthotropic symmetry of filtration properties, or in the main frame of reference, which obviously coincides with the principal axes of the tensor of absolute permeability, tensors $s_{ij}$ and $f_{ij}(r)$ have the form

$$s_{ij} = s_1 e_i^1 e_j^1 + s_2 e_i^2 e_j^2 + s_3 e_i^3 e_j^3, \tag{1.9}$$

$$f_{ij}(r) = f_1 e_i^1 e_j^1 + f_2 e_i^2 e_j^2 + f_3 e_i^3 e_j^3, \tag{1.10}$$

where $s_\alpha$ and $f_\alpha$ are the principal values of tensor $s_{ij}$ and $f_{ij}(r)$ respectively; $e_i^\alpha$ – components of the unit vectors directed along the principal directions of the tensor, $e_i^\alpha e_j^\alpha$ – dyad, $\alpha$=1,2,3. Substituting expressions (1.9) and (1.10) in (1.7) and (1.8) gives the following formulas

$$r^{э}(n) = r_{ij}^{э} n_i n_j = \int_0^\infty r(f_1 n_1^2 + f_2 n_2^2 + f_3 n_3^2) dr, \tag{1.11}$$

$$k(n) = k_{ij} n_i n_j = \frac{1}{8}\int_0^\infty r^2 (s_1 f_1 n_1^2 + s_2 f_2 n_2^2 + s_3 f_3 n_3^2) dr \tag{1.12}$$

At present, the complex laboratory experimental studies of reservoir properties were held, taking into account the anisotropy of the formation, the reservoir of hydrocarbons (Dmitriev et al, 2012;. 2014; Kuzmichev 2013). The latter allows testing theoretical constructs on the results of laboratory tests.

2. **Experimental verification of generalization of a simple capillary model for anisotropic porous media**. To conduct laboratory experimental research we selected cylindrical core of laminated cemented sandstone with height and diameter of 100 mm, which was extracted and dried.

It was believed that the layering of sandstone is perpendicular to the axis of cylinder symmetry, so one of the main directions of permeability coefficients tensor were supposed to be known. To determine the main directions in the plane of layering we used instrument "Uzor 2000" (Dmitriev et al, 2012;. Kuzmichev, 2013). The instrument measured the velocity of ultrasonic waves through the side surface of the core in km/s in increments of 30° (Fig. 1).

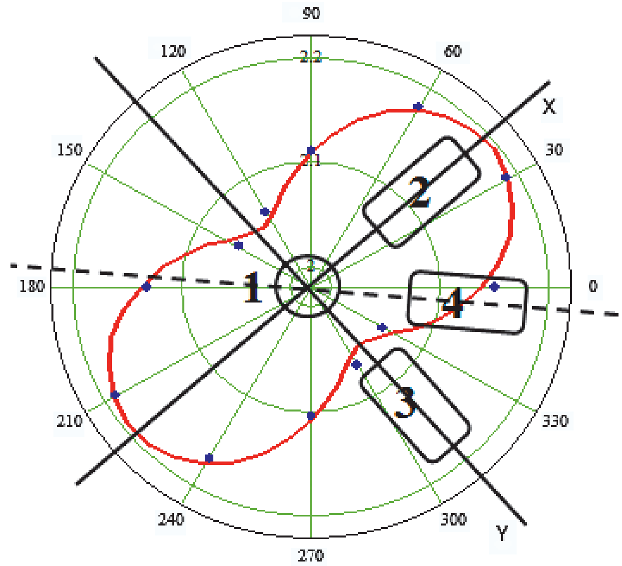

*Fig. 1. The velocity profile of ultrasonic waves in the core section; the location of the cut core samples of smaller diameter.*

The main directions of symmetric second-rank tensors defining material properties are consistent with extreme values of ultrasonic wave velocity (Dmitriev et al., 2014). According to the measurements we identified the main directions of the tensor permeability coefficients in the layering plane. Next, from the core source four smaller samples were sawn with 25 mm diameter and 30 mm in length. Three cores (samples 1 to 3) were sawn along the principal directions. The fourth sample is check on the bisector of the angle between the extreme directions.

The latter sample is used to test the hypothesis that the core symmetry axis coincides with the main direction of the permeability tensor and that the resulting values are indeed tensor components in the layering plane (Fig. 1). The figure shows the profile of the ultrasound for one section of the core. During sonic test of core it was noted that the main line changes slightly from one section to another over the entire height of the core. However, the maximum deviation does not exceed 10°, that, within the measurement error.

Further, porosity and absolute permeability were determined for all oriented samples in filtration of helium at atmospheric conditions. Permeability measurements were performed on a lab-tested scientific center of analytical and special core analysis of SC "VNIIneft". Measurement results are shown in Table 1. The repeated permeability measurements showed little change in the third decimal place.

Control sample, as noted above, is used to check tensor nature of characteristics: permeability, pore distribution density by radii. Let us check tensor nature of resulting permeability values. Using resulting values and $k_2$ we can calculate permeability value for all directions $k(\vec{n}) = k_{ij} n_i n_j$, find theoretical value $k_4$ and compare it with experimental value. Substitution of the numerical values in the formula for directed permeability gives $k_4 = 634 \cdot 10^{-15}$ m$^2$. Comparison of the theoretical and experimental values shows that the difference is less than 2%.

To obtain distribution curves of pore by radius we used CT scanner SkyScan 1172. Tomography scanner allows obtaining two-dimensional slices and three-dimensional models of pore space with high resolution (the resolution limit of 1 micron). In slices, by calculation we can obtain pore distribution density function by radii for each of the chosen direction. 1200 slices were made for each sample. The results are shown in Fig. 2-5.

According to the formula (1.7) we can calculate the effective radius of capillaries $r_\alpha^э$ for all directions and then from the equation $k_\alpha = s_\alpha \left(r_\alpha^э\right)^2 / 8$ we can determine the principal values of the luminal tensor sa. As a result, the following values were obtained of $r_\alpha^э$ и $s_\alpha$: $r_1^э$=5,0 micron, $r_2^э$=4,63 micron, $r_3^э$=4,69 micron, $r_4^э$=4,88 micron, $s_1$=22,1%, $s_2$=21,6%, $s_3$=24,3%, $s_4$=21,7%. According to formulas of directed values $r^э(n)=r_{ij}^э n_i n_j$ and $s(n)=s_{ij} n_i n_j$ we can compare the theoretical and experimental values of the tensor of the effective radii and luminal factor. Substitution of the numerical values in the formula gives the theoretical values of the effective radius of 4.82 micron and luminal factor 21.85%.

Comparison of the theoretical and experimental values shows that the difference is less than 2%.

A similar check is allowed by the pore distribution density function by radii. Comparison of the theoretical density function values of the pore by radius with experimental values for the control sample is shown in Fig. 5.

The latest series of studies was to determine the residual water saturation for the same oriented sample.

To convert laboratory parameters Hassler-Bruner method was chosen (Kuznetsov et al., 2010;. Mikhailov, 2008), allowing with a high degree of accuracy to determine the magnitude of capillary pressure at the outboard end of the sample, to estimate the corresponding saturation and build dependencies on capillary pressure and saturation. Results of the study are shown in Fig. 6 for samples in the direction of

| Sample | Porosity, % | Permeability by gas, mD ($10^{-15}m^2$) |
|---|---|---|
| «Z» (1) | 18,64 | ($k_3$) 668 |
| «X» (2) | 18,83 | ($k_1$) 689 |
| «Y» (3) | 18,74 | ($k_2$) 579 |
| «Control» - 45° (4) | 18,54 | ($k_4$) 644 |

*Table 1. The results of measuring the porosity and permeability on all core samples.*

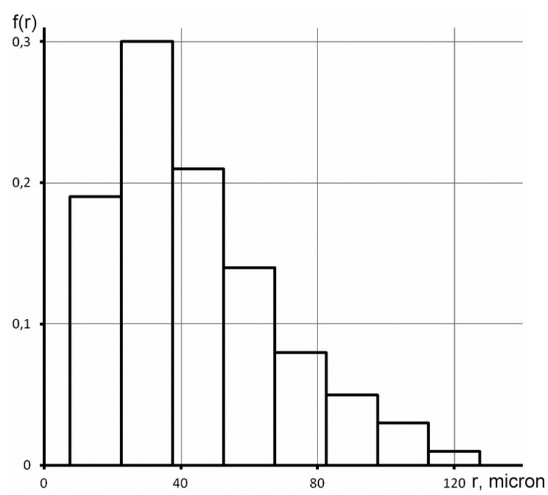


*Fig. 2. Histogram of pore distribution density function by radii for the sample oriented along the x-axis.*

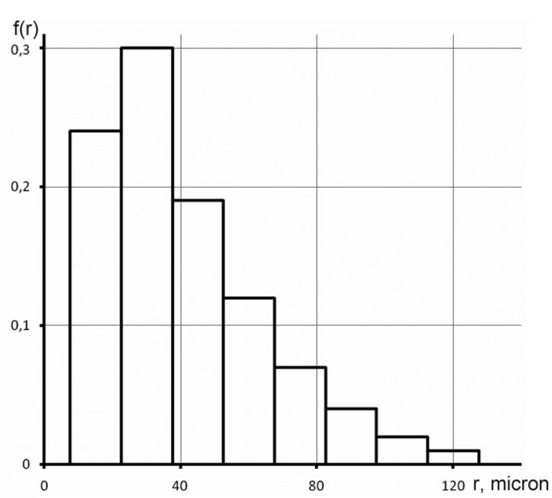


*Fig. 3. Histogram of pore distribution density function by radii for the sample oriented along the y-axis.*

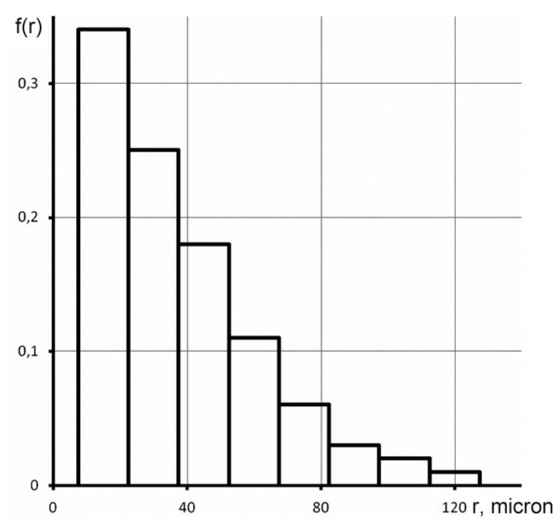


*Fig. 4. Histogram of pore distribution density function by radii for the sample oriented along the z-axis.*

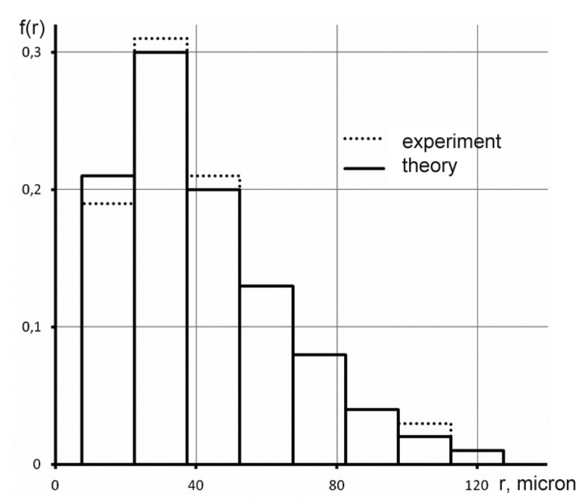


*Fig. 5. Histogram of pore distribution density function by radii for the control sample and comparison of theoretical and experimental histograms.*

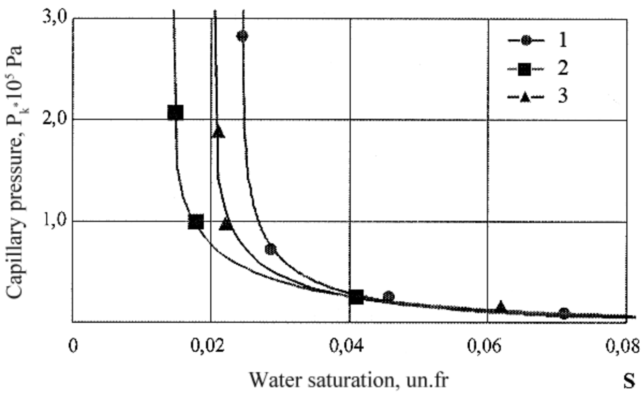


*Fig. 6. Dependence of the capillary pressure from water saturation for the X, Y directions and control sample. 1 – capillary pressure curve with the experimental points for the sample X; 2 – capillary pressure curve with the experimental points for the sample Y; 3 – capillary pressure curve with the experimental points for the control sample.*

X and Y in the layering plane and for control sample 4. The comparison results of theoretical and experimental values of capillary pressure on the control sample suggest tensor nature of the capillary pressure in anisotropic media.

An important consequence of this study is the effect of capillary pressure depending on the direction of flow. This implies that the capillary pressure is not a universal function of saturation for the anisotropic rock sample, but depends on the direction of flow, of the direction of stimulation. Confirmation of this fact requires further experimental and theoretical studies to identify the physical mechanisms of this effect, the structural characteristics of the pore space, the physical characteristics and physico-chemical interaction of 'fluid-rock' system, the nature of the layer wetting and other factors. The experiments should be repeatable for various rock samples at different scales of heterogeneity.

Let us note that the dependence of the relative phase permeabilities from the flow direction can be regarded as an established fact, confirmed by a number of experiments for clastic and carbonate samples with transversely isotropic, orthotropic and monoclinic symmetry of filtration properties; the tensor nature of the relative phase permeability is confirmed; their analytical dependence from saturation and structural parameters in different directions is obtained; a quantitative assessment is given for the contribution of the anisotropy effects in the performance with 'anisotropic' relative phase permeability included in a hydrodynamic model (Dmitriev et al., 2012;. 2014; Ter-Sarkisov et al., 2012, and a number of other publications).

## Conclusion

A generalization is made for presentation of simple capillary model of a porous medium in the case of porous media with anisotropic filtration properties. It is shown that for anisotropic porous media values of equivalent pore diameter, pore distribution, luminal factor and density function by radii depend on the direction and are set by symmetric tensor of the second rank. The results of the theoretical constructs are confirmed by laboratory experimental studies on the core.

The work is methodological in nature. The main objective was to establish the equivalence of the tensor representation of the capillary model to "geometrical" characteristics (porosity, luminal factor, pore distribution function by size) of anisotropic porous medium followed by applying an integrated research method of the core. Further development of this method is associated with the study of core samples of deep horizons (6-8 km).

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# Systematic Approach to Compare Technologies for the Enhanced Oil Recovery

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**Abstract**. The article deals with methodical approach to compare technologies of enhanced oil recovery on the basis of summarizing data of their implementation. The result of comparison is a ranking of technologies in decreasing order of technological and economic attractiveness. The recommendations for their definition are given. We discuss the features of attractiveness indicators under the conditions of PJSC Tatneft. It is shown that the technologies that are best for economic attractiveness do not turn out the best for the technological appeal. Recommendations are given on the preparation of data for calculation. The results of the ranking are described for a group of technologies designed to address one of the most common problems for the oil deposit development. It seems appropriate to compare technologies on the basis of a deeper evaluation of activities than is reflected in the statements.

**Keywords**: technologies of enhanced oil recovery, technological and economic attractiveness, attractiveness indicators, ranking of technologies.
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PJSC Tatneft has a wide range of different technologies to increase oil recovery performed through injection and production wells. The choice of technologies to be used is largely determined by information on previous experiences with their implementation, stored in Dll.dbf database of TatASU LLC for each activity. The aim of this work is to streamline the methodological approach to the comparison of technologies (characterized by average results of combined events) from these data. The approach is also valid in the case of own estimates of the outcome measures.

To compare the performance characteristics and to determine the best technologies we suggest using indicators of technological attractiveness (more justified in the aspect of providing more current oil production) and economic attractiveness (more interesting in the aspect of providing a given return on investment). Economic attractiveness is less strict, since in its assessment additional data are used with their own error in determining (cost of the activity, additional oil production for the timing of the effect, depending on the duration of the effect, which, in turn, is not free from the obligation to implement the investment program). Selection of the appeal depends on analyzing the problem to be solved.

Technological attractiveness indicator is calculated using the formula (1):

$$П_Т = Н \cdot К_{ТУ} \cdot \log М_Т, \qquad (1)$$

where $П_Т$ – indicator of technological attractiveness, units; Н – relative increase in oil production due to the activity, units; $К_{ТУ}$ – rate of technological success, unit; $\log М_Т$ – logarithm of the number of events considered for determining the technological attractiveness, units.

Technological success factor is calculated using the formula (2):

$$К_{ТУ} = \frac{М_Д}{М_Т}, \qquad (2)$$

where $К_{ТУ}$ – technological success factor, units; $М_Д$ – number of activities with a relative increase in oil production in excess of the threshold, units; $М_Т$ – the total number of activities considered for determining the technological attractiveness, units.

The indicator of economic attractiveness is calculated using the formula (3):

$$П_Э = Р \cdot К_{ЭУ} \cdot \ln М_Э, \qquad (3)$$

where $П_Э$ – indicator of economic attractiveness, units; Р – profitability of activities, %; $П_{ЭУ}$ – factor of economic success, units; $\ln М_Э$ – the natural logarithm of the number of activities considered for determining the economic attractiveness, units

Economic success factor is calculated using the formula (4):

$$К_{ЭУ} = \frac{М_Р}{М_Э}, \qquad (4)$$

where $К_{ЭУ}$ – factor of economic success, units; $М_Р$ – number of activities with profitability greater than the threshold, units; $М_Э$ – the total number of measures considered for determining the economic attractiveness, units.

Profitability, used as the main indicator of economic efficiency is determined by the commonly known procedure.

The cost of activities for the last years are reduced to the nomination of the year of analysis according to the formula (5):

$$З = З_t \cdot I_{t_М+1} \cdot I_{t_М+2} \cdot \ldots \cdot I_{t_А}, \qquad (5)$$

where З – costs for the activity given to the year of analysis, rubles; $t_М$ – year of ; $t_А$ – year of analysis; $З_t$ – costs for the activities in the year of its implementation, rubles; I – average inflation indices, units.

Technologies are ranked according to the attractiveness indicator.

The procedure for the formation of generalized notions of technological processes efficiency for reporting data is as follows.

Initially additional processing and preparation of database information is performed. Activities with questionable composition of reagents, physically incorrect data on the flow rate and water cut are eliminated of the array of data on the interested technologies.

For more adequately characterization of the technology objects (sites, wells) are excluded from consideration with a too short period of manifestation of the effect (effect is not yet fully emerged) and too long term of manifestation of the effect (the accuracy of determining the end is getting worse with time elapsed from the date of the activity). From the experience: 6-24 months on activities through production wells, 12-48 months on activities through injection wells. For the remaining activities control testing is carried out for accounting changes in pump performance during the activity (the amount of oil flow before the exposure and the average for the period of existence of oil flow growth should not exceed the flow rate prior to exposure).

In addition, by exposure through injection wells activities are derived from a consideration, characterized by the highest additional oil production for the following reasons. For activities through injection wells TatASU calculated the exposure by the accumulated operating parameters of wells with the use of two-parameter approximating functions. Usually a convex or concave curved 'path of points' in the background of the activity (roughly – 'arch') is replaced by a straight line. This predetermines systematically introduced mistake in predicting, respectively, in favor of or against the effect of the exposure.

In the latter case it is mathematically possible to obtain a negative value of the calculated effect, which, however, is not indicated in the report (zero is stated). Therefore, it is necessary to eliminate approximately the same number of events with the largest effect in order to compensate in the formation of activity selection to determine the average characteristics of the activities.

To describe the process average values are used for the set of indicators of the activities. They are liquid flow rate prior to exposure; oil flow rate prior to exposure; water cut before exposure; the duration of manifestation of the effect; additionally produced oil; costs of action (taking into account inflation over time); number of agents used in exposure (in the case of matching technology with similar composition used). Key features of the application of activities are the relative increase in the average daily oil flow rate (taking into account the above mentioned revisions) and the profitability of the activity application.

Let us note that the first one is a little more objective, since the main uncertainty in the technological efficiency is brought by the manifestation duration of the effect. Whereas the objective of the second indicator is deteriorating not only for the manifestation duration, but also for the difference in the inflation coefficients at different times of the activities included in the technology selection.

Calculation of indicators of technologies comparison is performed in the following order.

A list of compared technologies is defined. For each technology average growth of oil production rate, duration of effect, additional oil production, profitability are determined; technological success, economic success are calculated. By itself, economic success does not represent a serious interest, so the rigidity requirement of compliance of economic data to current economic conditions at the time of the analysis may not be overly restrictive. It is important to perform the mutual ratio of the economic success of technologies to determine the ranking of a particular technology in the general list of close technologies for a particular type of work. Based on these indicators, taking into account the representativeness, technology attractiveness indices are calculated, and their ranks are determined in the list of the considered technologies.

The presented approach to the comparison of methods is illustrated with examples of technologies comparison designed to solve the same task with several different ways (mainly used with reagents). In this paper, in order to avoid conflict of interests, titles of technologies are encoded though the indicators of activity applications are real.

The source of information is the statistical reporting database of TatASU – Dll.dbf. Database as of 01.01.2016 contains information about 8475 activities in total of 62 considered technologies.

The control testing is performed of indicators of the reporting on the application of activities:

- On the composition of reagents used to detect and reject activities, sharply differing in purpose (there is no reason to believe that the basic functional problem is solved in the technologies group – 397 activities);

- Under the terms of the exposure implementation to detect and reject activities, sharply differing in purpose – 164 activities with water cut of 20%, for the 68 activities water cut is not indicated;

- By the method of evaluation of exposure results to detect and reject activities whose results are distorted by errors – for 2646 activities change of the pump performance is not considered; for 214 activities the duration of the effect is more than 60 months.

In addition, for the above reasons 44 activities were rejected with duration of the effect less than 4 months or unspecified duration; 18 activities for other reasons.

Thus, for further consideration 5133 activities are left.

Results for ranking technologies by technological attractiveness are given in Table 1. Technologies with the number of activities less than 20 were considered insufficiently representative and were not ranked.

The ranking results on economic attractiveness are shown in Table 2.

The tables show that the best technologies on the economic attractiveness are not the best in the technological appeal. This should be taken in addressing issues of selecting technologies. Tables 1 and 2 show that the top of the ranking places technologies with codes 3122221524, 3121114282, 3122111752, widely used at present.

It should be noted that the above approach to assessing the effectiveness of activities has its own scope of applicability and is not free from principle drawbacks, mainly relating to the procedure for evaluation of technological activities and the procedure for calculating the economic efficiency of activities.

Regarding the use of materials of Dll.dbf database let us point out the following features.

First of all, it is the lack of consideration of the remaining completely out of sight changes in water intake, which is essential for water limit technologies, and it is very important for stimulation and displacement technologies.

Furthermore, in some instances, doubts are raised for correct forecast 'base' for a period exceeding the approximation interval (which is usually not prolonged).

| Technology code | Number of activities | Rank | Ratio of water cut after and before exposure, un. | Relative increase in oil production of well, un. | Technological success, un. | Technological attractiveness, un. |
|---|---|---|---|---|---|---|
| 3122221524 | 131 | 1 | 0,87 | 8,4 | 0,9 | 16,3 |
| 3121114282 | 757 | 2 | 0,89 | 5,5 | 0,9 | 14,9 |
| 3122111752 | 332 | 3 | 0,91 | 5,1 | 0,9 | 11,0 |
| 3122212713 | 65 | 4 | 0,90 | 6,8 | 0,8 | 10,5 |
| 3122117592 | 341 | 5 | 0,93 | 3,6 | 0,9 | 8,2 |
| 3122229244 | 294 | 6 | 0,88 | 3,5 | 0,9 | 8,0 |
| 3122114862 | 516 | 7 | 0,93 | 3,2 | 0,8 | 7,3 |
| 3122228994 | 34 | 8 | 0,91 | 4,8 | 1,0 | 7,2 |
| 3122111792 | 17 | 9 | 0,85 | 5,9 | 0,9 | 6,5 |
| 3122119752 | 70 | 10 | 0,90 | 3,9 | 0,9 | 6,3 |
| 3122117392 | 77 | 11 | 0,96 | 4,0 | 0,8 | 6,0 |
| 3121118962 | 410 | 12 | 0,92 | 2,7 | 0,8 | 6,0 |
| 3122111572 | 22 | 13 | 0,90 | 4,6 | 1,0 | 6,0 |
| 3122118372 | 182 | 14 | 0,94 | 3,2 | 0,8 | 5,8 |
| 3122118632 | 79 | 15 | 0,91 | 3,3 | 0,9 | 5,5 |
| 3122118822 | 158 | 16 | 0,92 | 3,0 | 0,8 | 5,3 |
| … | … | … | … | … | … | … |

*Table 1. The ranking results of technologies for technological attractiveness.*

| Technology code | Number of activities | Rank | Ratio of water cut after and before exposure, un. | Profitability of activities, % | Economic success, un. | Economic attractiveness, un. |
|---|---|---|---|---|---|---|
| 3121111992 | 48 | 1 | 0,93 | 39 | 0,88 | 1,34 |
| 3122229794 | 31 | 2 | 0,81 | 38 | 0,90 | 1,20 |
| 3122111572 | 22 | 3 | 0,90 | 29 | 0,86 | 0,79 |
| 3122117592 | 341 | 4 | 0,93 | 18 | 0,71 | 0,76 |
| 3121114282 | 757 | 5 | 0,89 | 16 | 0,69 | 0,73 |
| 3122229244 | 294 | 6 | 0,88 | 16 | 0,70 | 0,66 |
| 3122111752 | 332 | 7 | 0,91 | 13 | 0,67 | 0,50 |
| 3122221524 | 131 | 8 | 0,87 | 11 | 0,68 | 0,37 |
| 3122211953 | 44 | 9 | 0,92 | 12 | 0,68 | 0,30 |
| 3122111792 | 17 | 10 | 0,85 | 15 | 0,71 | 0,30 |
| 3122119302 | 31 | 11 | 0,90 | 12 | 0,68 | 0,28 |
| 3121111632 | 17 | 12 | 0,93 | 17 | 0,59 | 0,28 |
| 3122212713 | 65 | 13 | 0,90 | 8 | 0,71 | 0,25 |
| 3122111662 | 24 | 14 | 0,91 | 9 | 0,75 | 0,22 |
| 3122227124 | 138 | 15 | 0,86 | 5 | 0,59 | 0,16 |
| 3122228994 | 34 | 16 | 0,91 | 6 | 0,56 | 0,13 |
| … | … | … | … | … | … | … |

*Table 2. The ranking results of technologies for economic attractiveness.*

In perspective it seems appropriate to carry out a comparison of technologies based on a deeper assessment of the results of activities.

## Conclusions

1. To compare technologies according to their applications we suggest using indicators of technological attractiveness (more justified in the aspect of providing additional current oil production) and economic attractiveness (more interesting in the aspect of providing a given return on investment).

2. It is shown that the best technologies on the economic attractiveness do not turn out the best in the technological appeal.

3. The above approach to assessing the effectiveness of activities is not free from drawbacks, mainly relating to the procedure for evaluation of technological activities and the procedure for calculating the economic efficiency of activities.

4. It is advisable to carry out a comparison of technologies on the basis of a deeper assessment of activities than is reflected in the report.

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# Experience in the Application of Water Shut-off and Remedial Cementing Technologies in Fractured Carbonate Reservoirs

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**Abstract**. The early flooding of reservoirs by the most permeable interlayers in fractured zones is the downside of oil deposits development in carbonate rocks. Conventional methods of water shut-off and remedial cementing used for clastic reservoirs are not universal. This situation determines the need to find and apply new effective methods of enhanced oil recovery, diverter technologies, compositions for water shut-off and remedial cementing in the reservoirs with natural and artificial fracturing. The article shows the results of works performed on water shut-off and remedial cementing in wells, the section of which consists of fractured carbonate reservoirs.

Technologies are noted that showed positive technological efficiency. Application of viscoplastic silicate gels, technologies using high-viscosity oil and hydrocarbon-based cement slurries are the most technologically advanced and relatively low-cost.

**Keywords**: carbonate reservoir, water shut-off, remedial cementing, water shutoff composition, silicone grouting materials,  oil-based cement slurries; silicate viscoplastic gels, polymeric compositions

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Today, experience in the development of carbonate reservoirs is already more than 60 years, which is quite extensive and successful; problem of oil production from carbonate deposits is covered in the scientific literature widely enough.

At the same time, the results of scientific research in the development of carbonate reservoirs are poorly applied in practice. On the one hand, this is due to conventional approaches in the development of carbonates, formed in the period of mass development of highly productive clastic deposits. On the other hand, a variety of geological conditions of carbonate deposits, their properties and characteristics complicate the development of universal optimal technologies for reserves development.

The main feature of the geological structure of carbonate reservoirs is their complex reservoir properties, reflecting the simultaneous presence of voids of various types (cracks, voids, pores). The downside of operating process of oil deposits in fractured carbonate rocks is the early flooding of reservoirs on the most permeable zones (Smekhov, 1974; Tkhostov et al., 1970).

This situation determines the need to find and use in reservoirs with natural and artificial fracturing of new effective methods of enhanced oil recovery, flow diversion technologies, water shut-off compositions and remedial cementing.

In this article we present the results of works on water shut-off and remedial cementing in wells, the section of which is represented with fractured carbonate reservoirs.

The peculiarity of the works on water shut-off and remedial cementing in carbonate reservoirs is that by using aqueous solutions of chemicals, with high penetrating capacity (viscosity of the working solution is close to the viscosity of water) there is no firm adhesion of formed watertight compositions to a hydrophobic porous medium. Cement slurries containing a part of $CaCO_3$, are related to carbonate reservoirs, but because of the large dispersion of the particles have a limited penetration.

Conducting work using hydrocarbon-based cement slurry is perspective in this context (Magadova et al, 2015;. Efimov, 2011; Gaevoy et al, 2012). Their development began in the 1960s in the Russian State University of Oil and Gas named after Gubkin. Currently there are two groups of hydrocarbon-based cement slurry in the market: waterless and emulsion; each is characterized by its own peculiarities. Depending on the fineness of the cement mixture there are three brands of anhydrous hydrocarbon-based cement slurry: “Standard”, “Medium” and “Micro”. Areas of application in the first place, are determined by the type and injectivity of wells. For example, in the carbonate fractured reservoirs with well injectivity 720 m3/day and higher it is better to use the brand “Standard”, and in clastic and carbonate reservoirs with injectivity of 100-150 $m^3$/day – “Micro”.

The State University of Oil and Gas after Gubkin developed its own selective isolation technology (Efimov, 2011). The main material used in its water-free oil is the most accessible and cheapest selective material in the fields.

Anhydrous cement slurry and hydrocarbon liquid contribute to the formation of high strength and low permeability cement rock with a high degree of adhesion to the rock. Hydrocarbon-based anhydrous cement slurry (HBACS) is cement suspension (48-80 %) with a surfactant composition (0.2-0.5 %) in special hydrocarbon liquid (19.8-41.5 %). After entering water-containing medium the hydrocarbon liquid is substituted with water, HBACS is converted into a thick paste, and then into high-strength and tight cement. Without contact with water the solution is not thickened, separated; it retains their properties over 10 hours. Special hydrocarbon liquid of HBACS can be replaced by oil.

To ensure quality repairs on water inflow isolation in wells with high water cut it is necessary to upload hydrocarbon surfactant solution (emulsion composition) prior to HBACS, which pushes water from borehole, water-repellents the surface of conducting channels and forms a protective shield reverse to water movement into the well through the formation of highly viscous inverse emulsion. Upon contact with oil the emulsion drastically reduces its viscosity and is washed out from oil-conducting channel. Emulsion composition consists of 80% oil, 15% fresh water and 5% surfactant-repelling agent "Neftehimeko".

Tests on HBACS were carried out in 2008-2009 in the wells of JSC "Orenburgneft", containing in the section carbonate reservoir section with injectivity on the water of 550-700 $m^3$/day (Table 1) (Efimov, 2011; On the application of new materials ... 2013). In almost all the wells marked increase in oil production and reduced water cut. Dynamics of production rate and water cut in the well 57 of Dolgovsky field in 2008-2010 showed that the use of HBACS provides long-term effect.

Selective isolation technology was tested in 2010 in LLC "RN-Purneftegas" and JSC "Gazpromneft-NNG" in wells of Barsukovsky and Sugmutsky fields with water content of 93.6 to 99%. The liquid flow rate of individual wells before remedial cementing was 350-800 $m^3$/day, while oil production does not exceed 8 tons/day. As a result of the selective isolation water content is reduced and oil production is increased.

The paper (Kadyrov et al., 2010) describes the experience of the application of high-viscosity oil for water shutoff in carbonate reservoirs.

One of the strategic directions of PJSC Tatneft is to engage in the development of the reserves of heavy and bituminous oil. This oil on its physical-chemical parameters is prospectively to use in the water inflow control technology in carbonate reservoirs (Kadyrov et al, 2008;. Kandaurova et al, 2008). The developed technology is based on the injection into the insulated layers of oil-well portland cement suspension in a preheated mixture of high-viscosity oil in North and South domes of Mordovo-Karmalsky field. Oil at 20°C has a density of 935-949 kg/m3, dynamic viscosity of 360-4200 mPa*s (at 20 °C) to 14-60 mPa*s (at 80 C). Used mixture of oil has a density of 940-942 kg/$m^3$ at 20 °C and dynamic viscosity of 480-500 mPa*s (at 20 °C) to 17-18 mPa*s (at 80 °C).

When suspension enters the watered formation, plugging of water flow channels occurs due to cement hardening. In oil saturated intervals suspension is diluted with oil and washed out of the reservoir, indicating on the technology selectivity. Insulation screen in the initial period of formation can withstand the current pressure drop due to multiple increase of the viscosity of heavy oil when it cools to the temperature of the reservoir.

In order to prevent cooling of the suspension during the injection into formation, special insulated pipes are used with screen-vacuum insulation type (thermocase). Each tube consists of inner and outer tubes, in the annulus vacuum is made of 1 x 10 4 mm Hg, acting as a thermal insulation layer. Thermally insulated pipes are interconnected with coupling with an insulating sleeve. When pumping the heated water at a rate of 4 l/s through the insulated tubing string with length of 1000 m the temperature is reduced by 2 °C.

This technology was tested in the fields of oil and gas production department Leninogorskneft in 20 wells of 301-303 deposits of Romashkino field confined to Vereiskian, Bashkir and Serpukhov carbon deposits with a complex geological structure. Carrying water shutoff in the geological and technical conditions of these deposits is a challenge, and the majority of the previously used technologies are inefficient. The results of the proposed technology are presented in Table 2 (Kadyrov et al., 2010). Average oil production per well increase of 1.6 t/d, additional 5091 tons of oil is produced. The average duration of the current effective period is 158 days.

Both options of technologies can be used during water shutoff in both carbonate and clastic reservoirs, including alignment of wells injectivity profile.

The work (Kadyrov et al., 2014) provides a method to reduce water flow using water-swellable polymers.

Application of the most water-swellable polymer options is inefficient, as they swell in water indefinitely. Unlimited swelling effect leads to a reduction of the method duration. Currently used grades of water swellable polymers almost don't swell in highly mineralized formation water. Thus, the extent of absorption from the swellable polymers currently used in PJSC Tatneft of series AK-639, brands V415 and V615 in the mineralized formation fluids is significantly reduced, which limits their field of application and complicates the process. Elastomers (polymers having elastomeric properties

| Well No. | Filed | Liquid flow rate, $m^3$/day | | Water content, % | | Oil production, $m^3$/day | | Flowing level, m | |
|---|---|---|---|---|---|---|---|---|---|
| | | before remedial cementing | after remedial cementing | before remedial cementing | after remedial cementing | before remedial cementing | after remedial cementing | before remedial cementing | after remedial cementing |
| 57 | Dolgovsky | 80 | 60 | 92,5 | 65 | 6 | 21 | 1200 | 1000 |
| 340 | Sorochinsko-Nikosky | 168 | 175 | 75 | 65 | 42 | 68 | 2000 | 1522 |
| 566 | Sorochinsko-Nikosky | 62 | 103 | 57 | 57 | 26 | 58 | 1950 | 1528 |
| 527 | Berezovsky | 100 | 20 | 95 | 24 | 4 | 13 | 143 | 238 |
| 1031 | Bobrovsky | 26 | 75 | 75 | 85 | 5,3 | 9,3 | 989 | 1166 |

*Table 1. The test results of hydrocarbon-based anhydrous cement slurries on JSC "Orenburgneft" in 2008-2009.*

in operating range) based on the water-swellable rubber and urethane crumbs also swell poorly in formation water; furthermore, such products have a very high cost.

In this regard, Saratov factory of acrylic polymer "AKRIPOL" designed swellable acrylic copolymer, the molar fraction content of sodium acrylate a = 0.3 and the degree of crosslinking in the range m = 0.01-0.05 % (mole) (Bayburdov et al. , 2009). In experiments to determine the insulation coefficient samples were used of dried and crushed gel copolymer prepared in the laboratory by copolymerization of acrylamide and sodium acrylate in concentrated aqueous solutions (with a mass concentration of 20%) in the presence of a hydrophobic acrylic copolymer, crosslinker (N, N'-methylene-bis-acrylamide) and redox initiator system (ammonium persulfate and sodium metabisulfite).

The degree of swelling in fresh water is up to 2000%, and in the formation of up to 1200% for 24 hours, which is quite acceptable for the preparation of water shutoff compositions. This water-swellable polymer reagent with the increased elasticity of water-swollen polymer particles is put on production according to TU No. 2216-016-55373366-2007 marked with V 50E (Table 3).

The technology with developed water shutoff system is implemented in the process of implementation of ODA in four wells of "Tatneft" (Kadyrov et al., 2014).

It was found that the use of water shutoff technology systems based on acrylic copolymer powder suspension of brand 50E in an aqueous solution of surfactant DP9-8177, allowing to keep plugging ability over a long period of time, is the most promising in fractured porous and cavernous fractured carbonate reservoirs at work on insulation of bottom water tributaries or complete isolation of washed layer.

At the same time, water-swellable polymer of series AK-639, which is a "hardwired" surfactant (FSUE Saratov Scientific Research Institute of Polymers), was previously tested in the fields of the Samara region and the Republic of Tatarstan and has shown good efficiency (Berlin, 2011; Kurochkin et al, 2006). Powder compositions of "hardwired" polymer AK-639 with concentration of 0.5-1 % were injected in small portions and pushed from well by water with density of 1.18 g/cm$^3$. This polymer is capable of absorbing water (1 g of water-swellable polymers – up to 100-400 g of water) and is used to align the injectivity profile of injection wells. Gelation occurred at approximately 70 °C only when in contact with water for 24-28 hours. Additional oil production in the surrounding additional wells was 3575 tons or about 7 thousand tons/ton of injected polymer solution. The duration of the effect is 1.5 years. The work (Ibragimov et al., 2015) presents the results of swellable packers to isolate sections of fractured horizontal wellbores.

High speed of wells watering characteristic for deposits 302-303 of Romashkino field, is linked to their geological

| Well No. | Date of treatment | Oil production, t/day | Liquid flow rate, t/day | Water content, % | Oil production, t/day | Liquid flow rate, t/day | Water content, % | Additional oil production, t | Average oil production, t/day | Operation time, days |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Before treatment | | | After treatment | | | | | |
| 37908 | 20.04.07 | 1,0 | 8,2 | 89,1 | 3,9 | 6,7 | 42,6 | 791 | 2,0 | 399 |
| 26462 | 19.07.07 | 0,1 | 6,1 | 98,6 | 2,4 | 4,8 | 50,7 | 153 | 0,6 | 242 |
| 26531 | 11.07.07 | 0,1 | 5,1 | 94,6 | 4,3 | 9,2 | 53,7 | 1072 | 3,2 | 335 |
| 15483 | 24.08.07 | 0,1 | 5,0 | 98,3 | 1,1 | 6,8 | 83,7 | 80 | 0,3 | 260 |
| 37539 | 14.09.07 | 0,2 | 4,0 | 90,2 | 2,5 | 4,3 | 40,7 | 597 | 2,2 | 275 |
| 38187 | 20.09.07 | 1,5 | 7,9 | 94,6 | 5,1 | 14,2 | 64,4 | 269 | 2,2 | 124 |
| 38222 | 02.11.07 | 0,2 | 14,2 | 99,1 | 4,8 | 14,2 | 66,3 | 128 | 0,8 | 169 |
| 38168 | 22.02.08 | 0,2 | 8,0 | 97,3 | 2,7 | 11,9 | 77,0 | 114 | 0,9 | 124 |
| 37985 | 09.02.08 | 0,4 | 7,5 | 95,5 | 3,0 | 9,6 | 69,2 | 168 | 1,2 | 137 |
| 26476 | 15.02.08 | 0,0 | 3,3 | 99,1 | 4,2 | 11,7 | 64,4 | 173 | 1,4 | 121 |
| 18067 | 30.01.08 | 0,0 | 8,1 | 98,2 | 3,6 | 9,8 | 63,5 | 384 | 2,7 | 140 |
| 37947 | 22.02.08 | 0,2 | 5,4 | 95,5 | 1,4 | 6,5 | 77,9 | 170 | 1,4 | 118 |
| 38305 | 08.03.08 | 0,6 | 8,9 | 95,5 | 3,3 | 11,8 | 72,1 | 139 | 1,3 | 110 |
| 37956 | 01.03.08 | 0,3 | 12,1 | 97,3 | 2,0 | 15,0 | 86,4 | 87 | 0,7 | 118 |
| 35807 | 17.03.08 | 0,5 | 6,4 | 95,5 | 3,2 | 10,9 | 70,3 | 266 | 2,7 | 99 |
| 42 | 07.04.08 | 0,2 | 3,0 | 99,1 | 2,3 | 2,9 | 20,9 | 46 | 0,7 | 67 |
| 38317 | 19.03.08 | 0,4 | 8,6 | 97,3 | 2,5 | 9,9 | 75,0 | 113 | 1,2 | 97 |
| 17523 | 12.03.08 | 0,5 | 11,8 | 94,6 | 3,6 | 17,9 | 79,7 | 169 | 1,6 | 106 |
| 38071 | 24.03.08 | 0,0 | 4,6 | 95,7 | 1,2 | 6,5 | 81,6 | 33 | 0,3 | 95 |
| 26694 | 10.06.08 | 2,5 | 13,8 | 82,1 | 5,8 | 9,9 | 41,0 | 139 | 4,3 | 32 |

*Table. 2. The results of the use of water inflow control technology in carbonate reservoirs with high-viscosity oil.*

| Model No. | Weight content of elements, %, in technological solution | | Isolation coefficient, %, through | | |
|---|---|---|---|---|---|
| | surfactant DP9-8177 | acrylic copolymer В 50Э | 24 hours | 6 mon. | 12 mon. |
| 1 | 0,1 | 0,5 | 95 | 93 | 90 |
| 2 | 0,3 | 0,8 | 96 | 94 | 91 |
| 3 | 0,5 | 1 | 98 | 96 | 95 |
| 4 | 0,5 | 1,5 | 100 | 98 | 96 |
| 5 | 0,5 | 2,0 | 100 | 99 | 98 |

*Table 3. The results of the solution testing for water shutoff, containing swollen particles of water-swellable polymers.*

features: high layered and zonal heterogeneity; low reservoir properties of rock matrix; the presence of cracks, by which mainly produced water is moving; increased oil viscosity; low gas-oil ratio. Construction and operation of horizontal wells and sidetracks with horizontal termination in such circumstances involves the risk of progressive irrigation of wells.

To isolate the fractured areas in the construction of wells in the framework field trials, the technology of horizontal shaft casing with swellable packer. TatNIPIneft together with SC "Kvart" (Kazan) developed rubber polymeric water-swellable elastomer to create a swellable packer (Kateyev et al., 2014). Water swellable packer with length of 1 m, outer diameter of 133 mm to 114 mm in the casing, a tube with inner diameter of 145 mm after swelling in water of different salinity withstands breakdown pressure of 10 to 25 MPa. It is resistant to acid composition, which is used in PJSC "Tatneft" for enhanced oil recovery.

Field tests of water swellable packers are conducted during drilling 35387g (Fig. 1a), 37852g and repair of wells 37972g (Fig. 1 b), 37783g, deposits 302-303 of oil and gas production department Leninogorskneft. After the packers drain as part of the liner casing their swelling and leak tightness is checked by fluid injection on a packer installed in the 'head' of the liner casing. Table 5 presents the operating results on (25.05.2015) for wells 35387g, 37852g and neighboring wells with different options of completion: a cemented liner with perforations; non-cemented liner.

The experience is interesting in the development of TatNIPIneft (Medvedeva, 2014) of APS technology, which is based on the use of reinforced polymer systems based on water-soluble polyacrylamide DR9-8177. Development was carried out in the direction of modifying the structure-forming compositions by the addition of reinforcing additives used to reinforce cement products (Babenkov, 2007). The following products were used as fillers: water-insoluble oxides of divalent metals (ZnO, MgO), inorganic silicate fibers (glass fiber production of Tatneft-Elabuga) and various fiberglasses (VSM of company "C Ireland", basalt fiber of LLC "Russian basalt").

The formulation of composition and technology on its basis were developed primarily for high-permeability clastic reservoirs and carbonate reservoirs of fractured and fractured-pore type for use in technologies to increase oil recovery and reduce water in production wells. The compounding composition is developed with optimal processing properties: the concentration of surfactants of 0.7% to 1.0%, metal oxide from 0.05% to 0.08%, chromium acetate from 0.06% to 1.0%, reinforcing fibers 0.05% to 0.3%.

The oil and gas production department "Leninogorskneft" conducted pilot projects in three producing wells 35298, 35599, 37828 of deposit 303, Romashkino field, penetrated carbonate reservoirs in Protvinskian horizon. After the work on the implementation of the APS technology there was a significant decrease in water cut and growth of oil production rate. The growth of oil production rate per wells 37828,35599,35298 was 5.8 $m^3$/day 2.7 $m^3$/day, 7.5 $m^3$/day, respectively; water content decreased by 86%, 40% and 70%, respectively. It is possible to draw preliminary conclusions about the success of field tests conducted.

One of the method on reducing the limit inflow of water of different nature in the production wells is the technology of pumping viscoplastic silicate gels, gel-forming silicate compositions based on liquid glass (alkali silicate gel) and crystalline sodium metasilicate (acidic silicate gels).

Silicate gel is formed with time at elevated temperature from low viscosity solutions and is a structured system,

| Well No. | Operating time, days | Interval of liner installation, m | Flow rate | | Water content, % |
|---|---|---|---|---|---|
| | | | of liquid, $m^3$/day | of oil, t/day | |
| Bashkir stage | | | | | |
| 35387г | 303 | 950-1126 (with packer "Kvart") | 4,4 | 2,95 | 26,0 |
| 35384г | 280 | 838-1022 | 13,0 | 0,17 | 98,5 |
| 35393г | 170 | 847-1047 | 2,5 | 1,99 | 12,0 |
| 37723г | 259 | 940-1165 | 11,3 | 5,43 | 47,0 |
| 37729г | 174 | 950-1123 | 1,6 | 1,27 | 12,0 |
| 37855г | 240 | 942-1110 (with packer TAM) | 12,8 | 5,57 | 52,0 |
| 37551г | 314 | 892-1169 | 12,9 | 1,63 | 86,0 |
| 37853г | 291 | 948-1094 | 12,7 | 1,61 | 86,0 |
| Protvinsky horizon | | | | | |
| 35391г | 281 | 766-1017 | 10,0 | 1,09 | 88,0 |
| 37852г | 332 | 887-1048 (with packer "Kvart") | 12,5 | 4,92 | 57,0 |
| 37854г | 251 | 933-1136 | 13,2 | 2,29 | 81,0 |

*Table 4. Operation results of wells 35387g, 37852g and neighboring wells with different variants of completion.*

sometimes additionally hardened with polymer (surfactant, hydrolyzed polyacrylonitrile). The resulting gel can withstand large pressure gradients. Silica gels are stable over time at elevated temperature and salinity.

The Saint-Petersburg State Mining University (Nikitin, Petukhov, 2011) developed an insulating compound called SPMI-1. Liquid glass with module 2.9 of the commodity form containing sodium silicate 46.77%, chromium acetate 55% of the commodity form and 55% fresh water were used as components. Total 80 formulations were prepared, which differed in concentrations of sodium silicate, chromium acetate and composition extract temperatures.

It was found that the formulations with most optimum characteristics of gel processing and strength have a concentration of 3.3% sodium silicate and 1.1-1.38 % chromium acetate on exposure to formation conditions for 24 hours. More accurate reactant concentrations are selected based on filtration experiments on core deposits samples.

The advantage of all silica gels is in the possibility of destruction in the well and reservoir conditions by alkali solutions. The most effective use of such compounds is for insulation of casing circulation and isolation of bottom water.

The works (Solovyev et al, 2011;. Provedenie remontno-izolyatsionnykh rabot..., 2013) considered remedial cementing in wells using RELCOM polymer composition on the fields of Udmurtia and the Urals-Volga region.

The scientific and production center "Complex-Oil", Ufa, has developed a new polymer reactant based on acrylic acid RELCOM, which is produced by the original technology. In the chemical composition compared to peers it has a wide range of functional groups in the macromolecule with minimal branching, therefore it has higher coagulating and adsorption activity that contributes to the formation of durable water shutoff screen (Solovyev et al., 2011).

Physical and chemical nature of the residue-forming technology with a polymeric reagent RELCOM is that in the reaction in situ of RELCOM with reagent-crosslinker heat resistant rubber-like precipitate is formed in the form of a sticky polymer mass having good adhesion to the reservoir and the cement stone, which is resistant to erosion by fresh and saline water. Solutions of polyvalent metal salt or brine water are used as reagents-crosslinkers.

Table 5 shows the results of the increase in oil production and reduction in water cut after the treatment of bottom-hole zone of producing wells at the fields Belkamneft by technology using polymer RELCOM.

The paper (Alonov, Bobrikov, 2009) presents previously published articles and reports that show the experience of the application of silicone grouting materials ACOR and compositions on their basis on Russian fields, the Republic of Belarus and the Republic of Kazakhstan. The generalized results and the criteria for the selective isolation of water inflows are considered, the efficiency of remedial cementing is analyzed to limit the water inflow in oil and gas fields, the ways and prospects are given for the development of organosilicone grouting materials.

The experience in the application of the material ACOR-BN 102 is shown on Zlodarevsky field of Perm Krai. The productive horizons occur at depths of 1050-1550 meters and are composed of carbonate (limestone and dolomite) and clastic (argillites, siltstones and sandstones) rocks. Effective thickness of layers is 2-3.5 m. The porosity (for well 310 of Kashirskian and Bobrikovian deposits) is 10-20 %, permeability is 0.33 mm$^2$, reservoir temperature of 23.5-27 °C, current reservoir pressure of 8.5 MPa, paraffin content of 3.3-3.5 %. Results of the technology test are shown in Tables 6,7.

The article (Lymar, 2011) reviewed the results of field tests in wells of oil fields of the Republic of Belarus, water shutoff compositions based on chemical reactants GPAN, OVP-1 and ACOR-BN 102, as well as a new method for the selective isolation and integrated technology.

Oil deposits of the Republic of Belarus for the most part are confined to the deposits of the Devonian system and presented on 85-90 % of the carbonate rocks (pre-salt and intersalt complexes). The depth of their occurrence vary from 2.000 to 4.000 m. Average values of effective thickness are in the range of 10-120 m, reservoir temperatures – 50-90 °C. Mineralization of associated and formation waters varies from 140 to 340 g/l.

Studies performed in BelNIPIneft revealed that the VIS on the basis of chemical reactants A-KOR-BN102, GPAN and OVP-1 to a greater extent of the tested chemicals meet the necessary requirements (Lymar, 2011; Lymar et al., 2007b; 2006; 2003).

| Well No. | Well operating indicators before treatment | | | Well operating indicators after treatment | | | Average daily oil production, t/day / oil flow rate increase, % | Decline of average daily water production, m$^3$/day / Decline of average daily oil production, % | Duration of effect, months |
|---|---|---|---|---|---|---|---|---|---|
| | Average daily production of | | | Average daily production of | | | | | |
| | liquid, m$^3$/day / water content, % | oil, t/day | water, m$^3$/day | liquid, m$^3$/day / water content, % | oil, t/day | water, m$^3$/day | | | |
| 6725 | 327,0/99,8 | 0,6 | 326,3 | 15,0/82,0 | 2,4 | 12,3 | 1,8/300 | 314/96,2 | 17 |
| 130 | 22,0/80,0 | 3,9 | 17,6 | 5,6/13,2 | 4,4 | 0,7 | 0,5/12,8 | 16,9/96,0 | 12 |
| 132 | 15,0/93,3 | 0,9 | 13,9 | 16,7/85,2 | 2,95 | 7,1 | 2,05/227,8 | 6,8/48,9 | 8 |
| 255 | 17,3/82,0 | 2,6 | 14,2 | 13,4/52,0 | 5,4 | 7,0 | 2,8/107,7 | 7,2/50,7 | 15 |
| 229 | 23,0/87,8 | 2,5 | 20,2 | 11,5/74,0 | 5,0 | 8,51 | 2,5/100,0 | 11,6/57,4 | 16 |
| 223 | 16,0/81,0 | 2,6 | 13 | 17,1/70,7 | 4,2 | 8,0 | 1,6/61,5 | 5,0/38,5 | 15 |

*Table 5. Main application results of RELCOM polymer on fields of "Belkamneft".*

| Deposits | Oil saturated thickness, m | Type of water cut | Injection volume, $m^3$ | Oil flow rate, t/day | | Water cut of production wells, % | | Duration of effect |
|---|---|---|---|---|---|---|---|---|
| | | | | before remedial cementing | after remedial cementing | before remedial cementing | after remedial cementing | |
| $C_{1v}$ | 3,3 | Bottom | 6,0 | 1,0 | 2,6 | 80,1 | 39,0 | More than 5 mon. |

*Table 6. The results of remedial cementing in production well 310 of Zlodarevsky field.*

| Deposits | Injectivity, $m^3$/day | | Injection pressure, MPa | | Duration of effect |
|---|---|---|---|---|---|
| | before remedial cementing | after remedial cementing | before remedial cementing | after remedial cementing | |
| $C_{1v}$ | 275 | 130 | 5,0 | 10,0 | continued |

*Table 7. The results of remedial cementing in injection well 304 of Zlodarevsky field.*

GPAN and OVP-1 are new domestic chemical reactants for water shutoff (Lymar et al., 2007b, 2006; Brilliant, Kozlov, 2000; Lymar et al., 2008). GPAN is hydrolyzed polyacrylonitrile with modified fructose sulfonol additives. OVP-1 is alkaline hydrolyzate of technological waste of polyacrylonitrile fibers modified with special additives. The raw materials are used for its production of waste of technical fiber "Nitron" and chemical fibers (KNOPS), the suppliers of which are Belarusian enterprises JSC "Polymir" and JSC "Belfa". ACOR-BN102 developed by SPC "Nitpo" organosilicone composition with various modifying additives (Lymar et al., 2007a).

Conducted field tests of new water-isolating compositions confirmed the high efficiency of the proposed technologies. Six well operations are performed (Lymar et al., 2007a). Consumption of water-isolating compositions ranged from 5 to 30 m3 per well operation. All works are successful technologically and economically profitable (Table 8).

In the development of new technological schemes and techniques of water limiting operations, tests are performed for the technology of selective isolation of water flow using water-isolating compositions based on chemical reactants ACOR-BN 102, GPAN and OVP-1 and injection of water-isolating compositions in the pulsating mode.

These technologies are easy to implement, have low labor intensity, lack of complex technological operations, requiring the use of high-level experts, short duration and cost. They included:

- Water-isolating compositions to reduce injectivity of the reservoir: 10 $m^3$ of CMC solution and 6 $m^3$ of viscous liquid buffer on the basis of surfactants;
- Residue-forming compositions: 90 $m^3$ of 50% solution "Lignopol" and 4.9 $m^3$ of solution "GPAN";
- Gelling compositions: 17 $m^3$ of solution PAA DR-9 (175 kg of commodity-based) with 1.7 $m^3$ of $Al_2(S0_4)_3$ (0.35 t of commodity-based) and 11.8 $m^3$ solution of reagent "ACOR-BN102".

Completed pilot tests of water inflow solation technology in a horizontal wellbore confirmed not only the effectiveness of the proposed selective waterproofing technology in terms of oil deposits of the Republic of Belarus, but also the efficiency of the developed water-isolating compositions based on chemicals GPAN and ACOR-BN 102 (Lymar et al., 2006) .

Another promising direction in the implementation of new

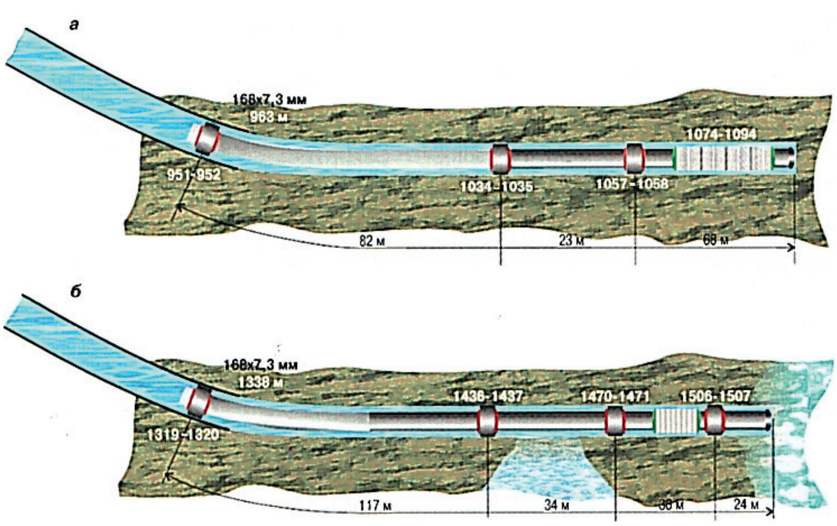


*Fig. 1. Layout of the liner in wells 35387g (a) and 37972g (b).*

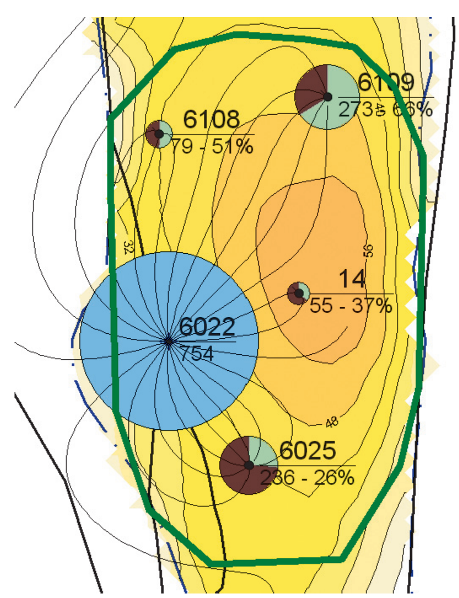


*Fig. 2. Map tile of current development conditions state in the area of well 6022 of Nyadeyyusky field as of 01.06.2008*

| Main chemical reactant of water-isolating composition | Well No. | Field | Type of activities* | Additional oil production, t | Average oil production, t/day |
|---|---|---|---|---|---|
| A-KOR-BN102 | 36 | Dubrovsky | OOI | 4891 | 3,4 |
| | 37 | Dubrovsky | OOI | 13027 | 4,5 |
| GPAN | 55 | Malodushinsky | OOI | 4556 | 2,8 |
| | 115 | Yuzhno-Ostashkovichsky | LZP | 4866 | 3,9 |
| OVP-1 | 144 | Yuzhno-Sosnovsky | LZP | 17121 | 14,3 |
| | 57 | Ostashkovichsky | OOI | 38944 | 24,2 |

*Table 8. The results of field tests when testing new water-isolating compositions in the wells of oil fields of the Republic of Belarus. * OOI – clipping of watered intervals, LZP – Abandonment of slaughtered flows.*

technological methods of isolation of water-inflow is tested in terms of wells the oil fields of the Republic of Belarus injection technology IPOs in the low-frequency pulsed exposure mode (Lymar et al., 2003).

The need for research in this area is due to the widespread introduction of water-isolating compositions with the contact mechanism of TM formation based on chemical reactants: hydrolyzed polyacrylonitrile, liquid glass, GPAN, OVP-1 and others.

Technology to reduce water inflow with similar water-isolating compositions includes sequential batch injection into the reservoir of residue-forming solutions and the precipitator (staple), separated by a buffer liquid. A special case is the reaction of water-isolating composition with the formation water. It is assumed that in the formation their mixing occurs to form a TM.

The effectiveness of water inflow insulation depends on the nature of the reagents and reaction mixing ratio (mass transfer) of solutions of residue-former and precipitator, which determines the amount and rate of the resulting reaction product, overlapping filtering channels.

One of the promising ways of increasing the effectiveness of work with the residue-forming compositions should be considered as the development of integrated technologies, including various methods of influence.

To enable mass transfer in porous media, uniform injection on the formation, increase in volume of formed TM, its strength and adhesion to rock, the injection technology of water-insulating composition into the formation in low-frequency pulsed exposure mode (Lymar et al., 2003).

New technology tests were carried out in the well 45 of Dubrovsky field. The effectiveness of the proposed technology is confirmed by comparing indicators of water-limiting operations made in similar geological and technical conditions of wells 45 (integrated technology) and 43 (standard technology) of Dubrovsky field. New technology compared to the standard one did not only increase the efficiency of water-limiting operations, but also reduces the consumption of water-insulating compositions by 2-3 times (Lymar et al., 2008).

Currently, on the oil fields of the Republic of Belarus pilot tests are conducted for the water-isolating compositions of the next generation on the basis of chemical reactants OVP-2 and various kinds of surfactants and coil tubing technologies. The paper (Ismagilov et al., 2013) shows the results of the application of waterproofing in cracks of carbonate reservoirs in deposits Val Gamburtseva. Key features of Nyadeyyusky, Cherpayusky, Khasyreysky deposits are presented in Table 9.

The main problems in the development of these deposits is a water breakthrough in production wells 2-3 months after the

| Deposit | Nadeyyusky | Cherpayusky | Khasyreysky |
|---|---|---|---|
| Reservoir type | Porous fractured cavernous | Fractured cavernous porous | |
| Average bedding depth (absolute depth mark), m | -2138 | -2404 | -2183 |
| Oil saturated thickness, m | 23 | 35,6 | 30,4 |
| Core permeability, $10^{-3}$micron$^2$ | 8,9 | 8,9 | 9,6 |
| Average porosity, un.fr. | 0,08 | 0,07 | 0,08 |
| Initial reservoir pressure, MPa | 23 | 25 | 23,8 |
| Initial reservoir temperature, ºC | 42 | 42 | 40 |
| Oil viscosity, mPa×s | 2,34 | 2,34 | 2,8 |
| Gas content, $m^3$/t | 127 | 117 | 102 |

*Table 9. Geological and physical indicators of deposits Val Gamburtseva.*

| Field | Number of well operations | Years of treatment | Additional oil production, thous.t | | |
|---|---|---|---|---|---|
| | | | Decrease of water cut | Stimulation of liquid withdrawal | total |
| Nadeyyusky | 20 | 2008-2012 | 141,3 | -35,2 | 106,1 |
| Khasyreysky | 11 | 2009-2012 | 93,0 | -30,6 | 62,4 |
| Cherpayusky | 4 | 2010-2011 | 5,2 | 0,4 | 5,4 |
| Total | 35 | | 239,5 | -65,4 | 174,1 |

*Table 10. The main application results of the technology on deposits Val Gamburtseva in 2008-2012.*

start of injection into injection wells along fractures, mainly in submeridian direction.

As an example, the results are giving of water inflow limitations in production wells by pumping composition of “strong gel” developed by LLC “RN-UfaNIPIneft” on the basis of polyacrylamide and stapler.

As the staple aluminum citrate [$C_3N_4ON\ (COO)_3$]A1 was used. Composition injection was carried out in the injection well 6022 of Nyadeyyusky field (Fig. 2).

During the execution of works 3 packs of the composition were injected at a concentration of surfactants 0.57% (insulation), 0.46% (squeezing) and 0.6% (strengthening), total – 1 000 $m^3$.

After the works completion there was a significant decrease in water cut of surrounding production wells (10-15 %) and the stabilization of oil production. Additional oil production amounted to more than 30 thousand tons.

In general, from the application of this technology in the fields of Val Gamburtseva in 2008-2012 additionally 174.1 thousand tons was produced with an average technological efficiency of 4.97 tons of additional oil per 1 well operation (Table 10).

## Conclusions

1. The complex reservoir properties of carbonate reservoir lead to early water cut on the most permeable interlayers in fractured zones in the exploitation of oil deposits.

2. The main objectives of improving the remedial cementing technology in carbonate reservoirs are reducing the cost and improving the efficiency of work, which can be solved in two main areas: the introduction of new water shutoff compositions and development of various technological schemes and techniques.

3. Conventional methods of water shutoff and remedial cementing used for clastic reservoirs are not universal, which determines the need to find and use in reservoirs with natural and artificial fracturing of new effective methods of water shutoff and remedial cementing.

4. Positive technological efficiency in fractured carbonate reservoirs showed the following technologies of water shutoff and remedial cementing:

- Cement slurries based n hydrocarbons;
- Heavy oil or bitumen for water shutoff;
- Water-swellable polymers;
- Swellable packers to isolate fractured sections of horizontal wellbores;
- Injection of viscoplastic silicate gels and polymer compositions;
- Silicone grouting materials ACOR and preparations based thereon.

5. The use of viscoplastic silicate gels, technologies using hydrocarbon-based cement slurries and high-viscosity oil are relatively low-cost and the most technologically advanced in comparable technological efficiency.

6. The development of relevant innovative complex technologies are perspective including both water shutoff and remedial cementing, as well as various methods of influence with the use of physical fields.

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# Identification of Leakage in Couplings of Tubing, Casing and Intermediate Casing for Wells of Underground Gas Storage in Salt Caverns by means of Spectral Noise Logging

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**Abstract**. This paper describes a survey conducted in an underground gas storage well that had excess annulus pressure. The integrated well survey including Spectral Noise Logging (SNL), High Precision Temperature (HPT) Logging and pulse electromagnetic defectoscopy determined the flow geometry in the cemented annuli of the well and identified leaking tubing and casing collars. The paper provides a detailed analysis of well logging data and workover recommendations. Analysis of information on flow and leaks obtained by the survey suggested that the well did not have to be suspended.

**Keywords**: Underground gas storage (UGS), excess pressure, Spectral Noise Logging (SNL), collar leak, High Precision Temperature (HPT) Logging, pulse electromagnetic defectoscopy, salt cavern

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## Introduction

Underground gas storages are modern facilities that ensure uninterrupted gas supply safety even during peak periods. Salt caverns are the most commonly used types of UGS in impermeable rocks.

This paper presents the results of employing High Precision Temperature (HPT) Logging, High Definition Spectral Noise Logging (SNL-HD) and EmPulse pulse electromagnetic defectoscopy as an integrated technology to detect leaks and determine the gas flow pattern in a multi-string salt cavern UGS well. Well integrity analysis based on these advanced technologies can reveal defects in downhole pipe strings, identify sources of excess annulus pressure (EAP) and trace gas flows behind several metal pipes. The obtained information can then be used not only to perform workovers in a particular well but also to produce recommendations for future casing of other wells and, thus, maximise their operating life and minimise workover time and cost.

## Technologies

### *High Definition Spectral Noise Logging (SNL-HD)*

The passive SNL technology is based on recording acoustic signals generated by the following processes:

- Fluid flow in the reservoir;
- Cross-flows in cement behind casing;
- Fluid leaks through completion components;
- Wellbore fluid and gas flows.

Subsequent analysis of SNL data in the time and frequency domains ensures an integrated approach to identifying casing and tubing leaks and fluid flow intervals.

The studies described in this paper were conducted with the SNL-HD-9 tool recording acoustic signals in a wide frequency range of 9 Hz to 58.6 kHz. The frequency resolution was 9 Hz below 5 kHz and 114 Hz between 0.1 kHz and 58.6 kHz, and the dynamic noise range was 90 dB. The noise spectrum contained 512 frequency channels, which ensured its high-definition rendering. The wide dynamic range of the recorded signals and the large number of channels make it possible not only to locate zones of elevated noise levels but also to differentiate their spectral compositions and identify their noise sources. For example, wellbore fluid flow generates mainly low-frequency noise, and fluid flow through the reservoir normally generates high-frequency noise.

Detailed descriptions of the wide-band High-Definition Spectral Noise Logging technology have been previously published in Detailed description of the technology of highly sensitive broadband spectral noise logging have been published previously  in (Maslennikova et al, 2012; Suarez et al, 2013; Aslanyan et al, 2015;. Marzouqi et al, 2012; Ahmed et al, 2015.).

### *High Precision Temperature (HPT) Logging*

HPT logging is one of the most informative well-surveying techniques to analyse well integrity. Its high accuracy is achieved by conducting measurements using a high-precision temperature measuring tool during downward passes.

If a well is shut in for a long time, a thermodynamic equilibrium sets in between the well and the surrounding rocks. For this reason, the downhole components of a well, including cement behind casing, do not have any substantial effect on the wellbore temperature measured at least several days after shut in, which is a static temperature profile.

The difference between the flowing and static temperatures is caused by fluid or gas flow through the reservoir, casing leaks or cross-flows between reservoirs. Temperature logging detects thermal anomalies caused by thermodynamic processes, such as fluid flow through the reservoir or wellbore, and their shapes are analysed to identify flow sources and patterns.

***EmPulse pulse electromagnetic defectoscopy***

Multiple casing strings and corrosive brine in tubing created a challenging environment to determine the wall thicknesses of the uncemented casing (177.8 mm), production casing (244.5 mm) and intermediate casing (324 mm). Well integrity control implemented in this survey, including the detection of corroded downhole components and collar location, was based on pulse electromagnetic defectoscopy using the EmPulse-3 logging tool, which can scan casing pipes as large as 355 mm in diameter. The EmPulse-3 tool emits strong magnetic pulses and analyses magnetisation decays in the time domain at each survey depth. The shape of a decay curve contains information on the diameter, electrical conductivity, magnetic permeability and wall thickness for all surveyed pipes. This information is obtained for each pipe by comparing the modelled and measured magnetisation decays at each sensor coil of the tool (Ansari, 2015).

## Brief well history and survey rationale

The well was drilled in April 2012 and put into operation in the same year to wash out salt caverns in several stages and subsequently operate an underground gas storage. In December 2013, an excess pressure of 64 kgf/cm$^2$ was observed in the 244.5/324-mm cement annulus (Fig. 1). In August 2015, pressure testing and bleeding from the 244.5/324-mm and 324/426-mm annuli confirmed their communication. The most recent wellhead annulus pressure measurements indicated excess pressures of 114 kgf/cm$^2$ in the 244.5-mm string, 58 kgf/cm$^2$ in the 324-mm string and 16 kgf/cm$^2$ in the 426-mm string.

## HPT-SNL-HD-EmPulse survey results

The integrated well survey showed that the excess pressure was caused by gas from the 177.8/244.5-mm annulus that entered the 244.5/324-mm annulus through a leaking collar in the 244.5-mm string at 203-m depth and the 324/426-mm annulus through a leaking collar in the 324-mm intermediate casing string at 133-m depth (Fig. 1). Another leaking collar was found in the 177.8-mm tubing at 157.3-m depth.

The noise amplitude change observed during pressure bleeding, a temperature anomaly and defectoscopy results confirmed the collar leaks in the 244.5-mm string at 203.0-m depth and in the 177.8-mm string at 157.3-m depth.

The collar leak in the 324-mm intermediate casing string at 132.4-m depth was associated with increased noise intensity during pressure bleeding. Noteworthily, high precision temperature sensors could not detect it because the flow rate was too high for the formation of a temperature anomaly. At the same time, the generated acoustic noise was high enough to be detected by the SNL-HD memory tool.

Alongside this, the EmPulse-3 survey demonstrated the ability of pulse electromagnetic defectoscopy to determine the wall thicknesses of the 177.8-mm, 244.5-mm and 324-mm strings.

## Conclusions

The HPT-SNL-HD-EmPulse hardware and software technology has been effectively employed to come up with the following solutions:

1) Location of tubing and casing leaks;

2) Location of the source of excess annulus pressure;

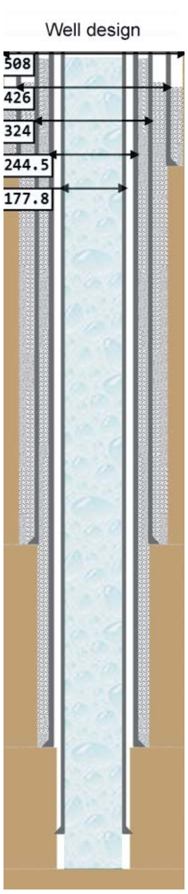
3) Tracing the gas flow path even behind several pipe strings.

Analysis of the integrated survey data identified the following causes of excess annulus pressure:

1) Poor cement bonding;

2) Incorrect selection of metal pipes in terms of corrosion resistance;

3) Inadequate sealing properties of pipe collars.



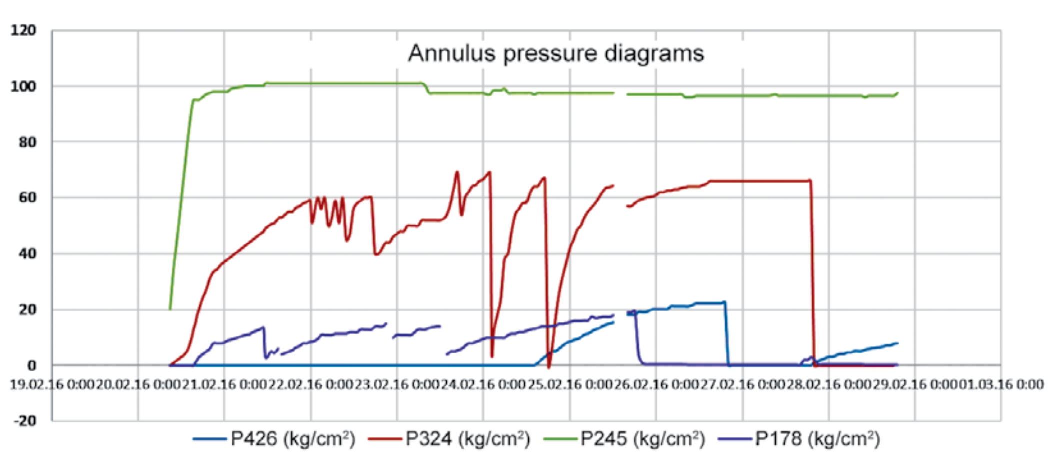




*Fig. 1. Pressure dynamics in the 177.8/244.5-mm, 244.5/324-mm and 324/426-mm annuli.*

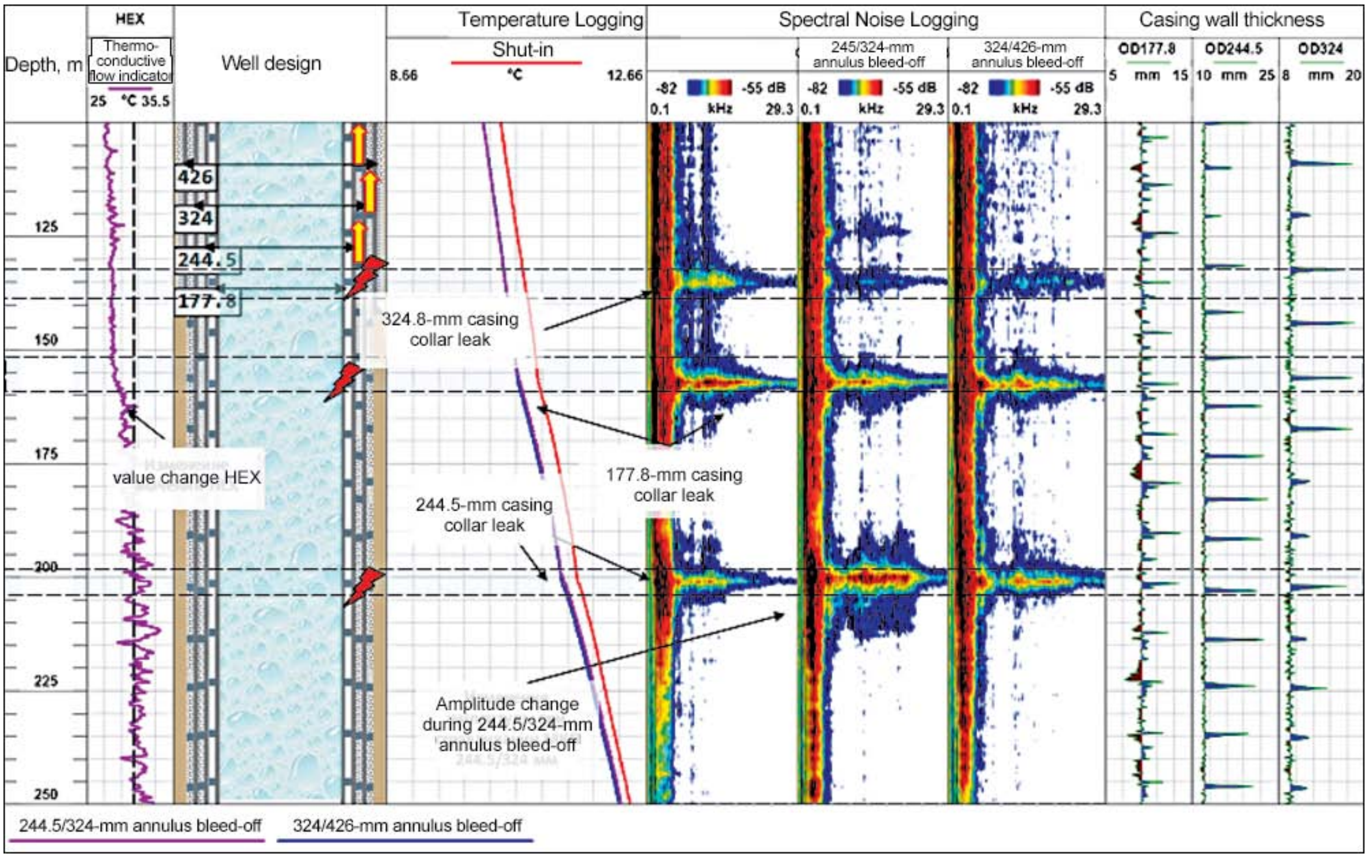



*Fig. 2. Cross-flows behind casing and collar leaks identified by the integrated well survey: (1) Temperature gradient and thermoconductive flow indicator data variations along with a high-amplitude noise anomaly at 157.3-m depth indicated a collar leak in the 177.8-mm string; (2) Spectral Noise Logging data detected a noise amplitude change in the depth interval 199-211 m during pressure bleeding from the 244.5/324-mm annulus, and temperature data from the depth interval 202.0-203.0 m indicated a temperature anomaly, which signalled a collar leak in the 244.5-m string at 203-m depth; (3) Noise observed in the interval 132-138 m was caused by a collar leak in the 324-mm intermediate casing string.*

The location and characterisation of the leaks enabled the operating company to avoid well abandonment and facilitated workover planning. The flow pattern observed during pressure bleeding from both annuli suggested that this flow could be eliminated by cementing the 177.8-mm string and setting an additional casing string.

## Abbreviations

SNL – Spectral Noise Logging
SNL-HD – High Definition Spectral Noise Logging
HPT logging – High Precision Temperature Logging
UGS – Underground gas storage
EAP – Excess annulus pressure

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# Generalization of Geological and Physical Characteristics of Fields Belonging to Oil-gas Production Department «Yamashneft» in order to Increase the Efficiency of Hydrodynamic Well Testing

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**Abstract**. Currently, the question of choosing the right approach for hydrodynamic testing and post-processing of the data is very important. The quality of the study and, respectively, data processing is influenced by various factors such as, lithological composition of rocks, their density, mechanical stress in the rock, hydrodynamic influence of rocks, filtration movement of fluids, pressure and temperature distribution in the formation. Fields of oil-gas production department "Yamashneft" are at the late stage of development, and the majority of wells are marginal. All these factors may affect the results of the pressure recovery curve processing, which often differ from the actual values of the state parameters of bottomhole formation zone, which means incorrect approach to research (recovery time of bottomhole pressure) and the choice of processing method.

Questions to obtain reliable information at a late stage of development are of particular importance, since on their basis significant technological and economic solutions are taken, such as shutdown of watered and marginal wells, technological measures to enhance the oil recovery factor are planned and implemented. During the well testing and interpretation of the data we must take into account the structure of the investigated layer, features of the pore space, geological and physical characteristics that will keep the correct calculation of reservoir properties.

To this end, the generalization of geological and physical data was made to divide fields into separate groups for the subsequent development of a methodology for each group, and select the optimum processing of results. Thus grouping of objects (lithological characteristics of reservoir, properties and composition of cement, type of porosity, permeability range, porosity range) causes a single, but a qualitative approach to conduct hydrodynamic well testing and the method of interpreting the results.

**Keywords**: hydrodynamic well testing, bottomhole formation zone, interpretation of hydrodynamic testing, geological and physical characteristics, porosity, permeability, change of filtration parameters, developed horizons.

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As a result of complex physical and chemical processes that occur in a long geological period, the producing formation acquires a certain structure. After its penetration by wells various processes occur and will occur in the bottomhole zone that violate or infringe the original equilibrium mechanical and physico-chemical state of the rock. These processes arise from the moment of the formation penetration, and as drilling extend deep into the bottomhole formation zone.

As a result, two zones are formed around the well: the 'skin' area, which is characterized by a radius $r_s$, permeability $k_s$, and distant part of the formation with the natural permeability k (Fig. 1).

There is a filtration of reservoir fluid through bottomhole formation zone in the well. If the same reservoir properties in the bottomhole zone change for some reason (improvement or deterioration) compared with the initial state of the formation, the well productivity also will be different compared to its natural value.

State of the bottomhole formation zone is determined by lithological composition of the rocks, their density; mechanical stresses in the rock; hydrodynamic influence of cracks; pollution of rocks and physico-chemical processes occurring in the reservoir; movement of filtration liquids, pressure and temperature distribution in the formation.

State of the bottomhole formation zone can be degraded in the primary and secondary drilling into the formation, well casing, jamming it in front of many repairs as well as during operation due to precipitation of asphalt-resin-paraffin deposits (heavy oil sediments) and inorganic salts in the pores of rocks, dirt by mechanical and other impurities.

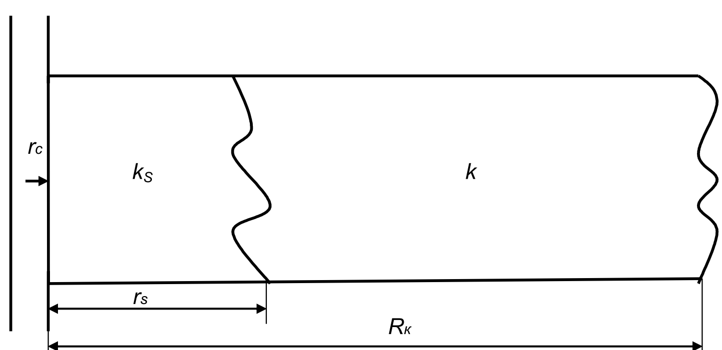


*Fig. 1. Distribution scheme of two zones around the wells.*

Changes in permeability around borehole space may reduce well productivity. This has a significant impact on the amount of fluid drag to oil flow when moving from the formation into the well.

As is known, the permeability changes in bottomhole formation zone are usually estimated by “skin-factor”. Its origin is due to the presence of altered permeability of the zone around the wellbore. Thus to overcome the arising resistance arising called ‘skin’, it is necessary to create higher pressures, thus limiting the energy capacity of the formation. As a result, the well productivity will decline (Andaeva, Sidorov, 2012).

Experience of oil and gas production department “Yamashneft” indicates a significant change in productivity of wells, and permeability during their operation (Fig. 2). In practice, the concept of oil and gas production, well productivity generally includes characteristic of production wells opportunities associated with both the reservoir properties of the productive horizons penetrated by the well, and its technical condition.

As seen from the graph, the productivity of the well No. 1276 of Shegurchinsky field decreased by 2 times in 10 years. During this period there have been no single event on the effects on the bottomhole formation zone.

Thus, the dependence is observed of the well productivity and dynamics of oil production in time (Fig. 3).

The specialist must have sufficient and accurate information about the formation, its energy capabilities, production opportunities for an adequate analysis of the development indicators and production prediction when implementing development projects. Most of this information can be obtained from the results of well studies in the unsteady modes.

Research on unsteady filtering modes (research by the pressure/level recovery, pressure drop, during the injection by method of level drop in the injection well and wells interference testing) is an integral part of petroleum engineering.

In practice, the possibility of a qualitative interpretation of well test results at unsteady conditions is often limited by:

1) lack of information;

2) lack of adapted techniques for the study of deposits with low-permeability reservoirs;

3) wrong choice and application of interpretation methods;

4) inability to properly organize the information, etc.

Most commercial engineers are faced with cases where for authentic interpretation accurate information is not enough on oil pressure and extraction of an earlier period, or the results of previous studies for comparison.

In general, a good rule is to conduct basic research on unsteady modes in production well soon after its completion and putting into operation after drilling. This facilitates early detection and prevention of many complications, of which only insufficient formation treatment is most apparent. Such studies also provide information about the reservoir parameters for mathematical modeling and baseline data for comparison in the event of complications in the formation and the well.

The presence of a significant fund of well with small and medium production rate, due to low water permeability of bed, leads to the fact that most of the level build-up curves are under-recovered. In addition to the short duration of withdrawal of such curves, significant drawback is usually in a small number of points on the level build-up curves. Under-recovery of curves affects the accuracy of determining the filtration parameters of the formation and the reservoir pressure.

As a result inaccuracy of the data complicates the ability to make a correct decision on conducting geological and technical measures aimed at restoring, improving or maintaining the existing level of filtration component in the bottomhole formation zone.

To determine the parameters of formation zone remote from the well, registration length of pressure recovery curve must be sufficient to eliminate the influence of ‘after-inflow’ (the continued inflow of fluid into the wellbore), and then an increase in pressure occurs only due to the liquid compression in the formation and its filtration from remote to the near formation zone (end portion of the pressure recovery curve).

The duration of the study of the production well by pressure recovery curves can range from a few tens of hours to a few weeks, so that the study range covers a large area

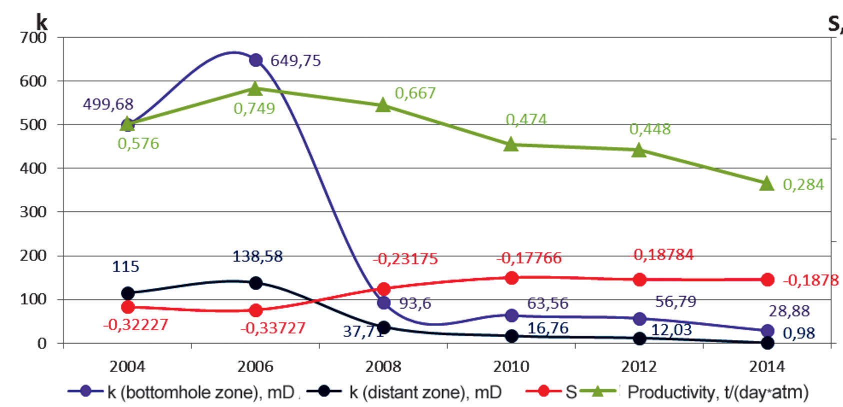


*Fig. 2. Change dynamics of filtration parameters, characterizing conditions of the bottomhole formation zone of the well No. 1276 of Shegurchinsky field.*

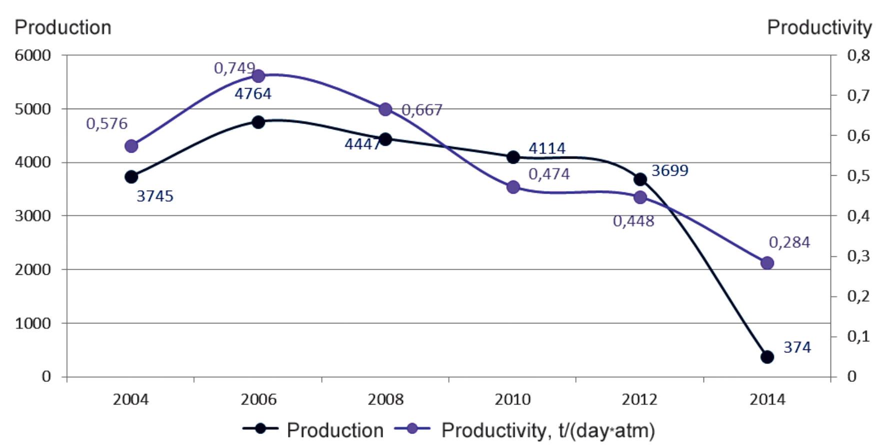


*Fig. 3. Dependence dynamics of oil production from the productivity of well No. 1276 of Shegurchinsky field.*

| Lithological characteristics of the reservoir | Properties and composition of cement | Porosity Type | Range of k, $10^{-3}$ micron$^2$ | Range of m, unit fraction | Field |
|---|---|---|---|---|---|
| 1 | 2 | 3 | | | 4 |
| **Tulskian Horizon** | | | | | |
| The reservoir consists of argillites dark gray, laminated, with interbedded sandstones and siltstones. In the middle of the horizon interlayer lies of limestone dark gray, finely crystalline, clayey. Sandstones are gray, dark brown, inequigranular, quartz, with oil saturated interlayers | The cement type (5-8%) is contact, cementing substance is secondary quartz and carbonate-clayey material | P | 421…1272 | 0,187… 0,25 | Tyugeevsky, Sirenevsky, Berezovsky, Shegurchinsky , Ekaterinovsky |
| The reservoir is presented by unconsolidated sandy-siltstone rocks | The cement type is contact, partly porous | P | 457…853 | 0,21… 0,23 | Ersubaykinsky , Arkhangelsky |
| The reservoir is presented by fine-grained sandstones, silty, partly clayey. Sandstones for 75-80% consist of quartz grains of intergranular pore space | Contact, interference | P | 532,5 | 0,208 | Krasnogorsky |
| Clastic rocks are argillites, siltstones and sandstones. Argillites are dark gray to black, irregularly silty; siltstone is dark gray, clayey, carbonaceous and calcareous. The sandstones are gray, brownish-gray to brown, calcareous. The layers of carbonate rocks are presented by dark gray argillaceous limestone | Cement is of calcite type, the type of filling is mainly incompletely porous, rarely crustified, and basal | P-C | 473 | 0,197 | Yamashinsky |
| **Bobrikovian Horizon** | | | | | |
| The reservoir is presented by quartz sandstone, fine-grained, interbedded with siltstone, mudstone, coals and carbonaceous shales, occurring mainly in 'incision' wells. Sandstones are dark brown, medium cemented, porous, heavily soaked with oil. Mudstones are brown to black, dense, with the remnants of charred plants. Shale is black, carbonaceous, with rare inclusions of pyrite | Cement is slightly developed, of quartz composition, distributed in the form of regeneration rims on detrital grains. Calcite and pyrite as a local cement are distributed quite widely, especially in formations of Tulskian age, but because of the local nature it has no appreciable effect on reservoir properties | P | 81…938 | 0,2…0, 32 | Shegurchinsky , Yamashinsky, Tyugeevsky, Sirenevsky, Berezovsky |
| Bobrikovian reservoir is represented by quartz sandstones fine-grained, with silty interlayers. Reservoir is interbedded with low permeable, clayey, sometimes calcareous, siltstones, impermeable mudstones. Reservoir type is porous. | The cement type is contact, partly porous | P | 220…1397 | 0,169… 0,242 | Ersubaykinsky , Arkhangelsky, Krasnogorsky |
| It is presented with interbedded sandstones, dark gray, oil-saturated and argillites dark gray, dense. Siltstones are dark gray, sandy, calcareous | The cement type is contact | P | 1100 | 0,23 | Ekaterinovsky |
| **Vereiskian Horizon** | | | | | |
| The reservoir is presented by carbonate and clastic (argillites, siltstones) rocks with a predominance of carbonate rocks (organic limestone interbedded with dolomite) in the lower part of the productive horizon | Cement of three generations: more crustified with a grain size of up to 0.03 mm, calcite or dolomite; late – unevenly cemented, small-medium-grained to 0.8 mm, calcite, porous or basal type | | 287…517 | 0,16… 0,166 | Yamashinsky |

*Table 1. Generalization of geological and physical data for fields of oil-and-gas production department "Yamashneft". F – fractured, P – porous, C – cavernous.*

| | | | | | |
|---|---|---|---|---|---|
| The lower pack is composed of limestone gray, brownish-gray, dark brown, organogenic-clastic, less crystalline granular, fractured, porous, interlayers of oil saturation (layers C2vr-5, C2vr-3 C2vr-2). Carbonate formations are separated by interbedded argillites dark gray, horizontally-layered, mica. Clastic pack is composed of interbedded mudstones, siltstones, among which there are rare interlayers of limestones | Cement type - contact, porous, crustified. Cement (10 - 40%) - micro–, fine- and small-grained calcite and clay material, its type - porous, crustified, rarely basal (sealed interlayers) | P | 15…280 | 0,13… 0,15 | Sirenevsky, Berezovsky, Arkhangelsky, Tyugeevsky |
| It is presented by organogenic-clastic limestone, slightly clayey, partly with thin interbedded mudstone. Top and bottom of layers is often clogged or sealed | Cement type is contact, presented with finely grained calcite | P | 218…227 | 0,168… 0,27 | Ersubaykinsky, Krasnogorsky |
| Lower - carbonate-clastic pack is represented by limestone light gray, fractured, with interbedded mudstones, oil saturation. Top - clastic pack is composed of mudstones greenish-gray with brownish tinge, dense, layered | The cement type is contact | P | 156 | 0,148 | Ekaterinovsky |
| It is presented by carbonate rocks. The lower part is composed of limestone gray, gray-brownish, organogenic-clastic, partly clay and dense with subordinate interbedded clays and silts. | The cement type is contact | P, F-P | 134 | 0,164 | Shegurchinsky |
| **Bashkirian Horizon** | | | | | |
| The reservoir is composed of limestone recrystallized, brecciated, cavernous, light-gray, brownish-gray, fine-grained, with smears of light green clay material on stylolite seams. Limestone is partly fractured, porous, interlayers or heavily soaked with oxidized oil. In some wells a significant portion of the Bashkirian top is eroded by Vereiskian ‘incision’ | Limestone is cemented with micro and fine-grained calcite. Cement type is porous, crusitified, partly basal, of quantity - 10 - 35% | P | 29,6…32 | 0,14… 0,16 | Tyugeevsky, Sirenevsky |
| The reservoirs are presented mainly with organogenic limestone, rarely organogenic-detrital and fine-grained limestone. Dolomites are present is subordinate number, there are also brecciated rocks and interlayers of calcareous sandstone | The cement type is contact, porous | P, F-P | 108 | 0.144 | Shegurchinsky |
| The reservoirs are presented mainly with organogenic limestone, rarely organogenic-detrital and fine-grained limestone. Dolomites are present is subordinate number, there are also brecciated rocks and interlayers of calcareous sandstone | Cement is not heavy, sometimes basal | F-C-P | 201 | 0.174 | Yamashinsky |
| It is presented by limestone gray, organogenic-clastic, clay, with interlayers fractured and cavernous, partly oil saturated | Cement is made of unevenly grained calcite, which is 10-20% of rock volume; cement type – porous, contact, regeneration, less- basal | P,F-P | 69 | 0,128 | Berezovsky |
| It is presented with limestones recrystallized, fine-grained, fractured, poorly clayey, partly plastered with rare inclusions of anhydrite. | Cement type is mainly crusified, contact, partly porous | P, P-F | 9,3…118 | 0,096… 0,148 | Ersubaykinsky, Krasnogorsky, Ekaterinovsky |
| It is presented mainly by limestone yellowish-gray, interlayers of organogenic-clastic, porous, with numerous stylolite seams, with some interbedded limestones dark brown, porous, fractured, cavernous, soaked with oil. It lies on the eroded surface of the Serpukhovskian formations | Cement is contact, porous, less basal, consists from 5 to 25% of rock volume | F-P | 193 | 0.13 | Arkhangelsky |

*Table 1. (Continued). Generalization of geological and physical data for fields of oil-and-gas production department “Yamashneft”. F – fractured, P – porous, C – cavernous.*

of the formation. However, during long-duration studies end portions of the pressure recovery curve may be distorted by the influence of neighboring wells on the pressure distribution in the remote zone of the formation.

Level build-up curves method is used, including, for wells with low reservoir pressure (with low static level), i.e. non-gushing (without overflow at the wellhead) or unstably gushing.

Duration of registration of level build-up curves or pressure recovery curve depends on the well productivity as a whole, fluid density, and hydrodynamic connection between the bottomhole formation zone and remote formation zone.

The processing results of pressure recovery curves often differ from the actual values of the bottomhole zone state parameters, indicating on the wrong approach to research (recovery time of bottomhole pressure) and choice of treatment method. A large part of the pressure recovery curves obtained in the study of fields of oil-and-gas production department "Yamashneft" does not meet the requirements under which their unique treatment can be carried out. Questions to obtain reliable information at a late stage of development are of particular importance, since based on them such important technological and economic decisions are taken, like shutting of watered and low-yield wells, technological measures to enhance the oil recovery factor are planned and implemented (Guidance document ... 2015; Karnaukhov, Pyankova 2010; Chodry, 2011).

Thus, to determine the application conditions of reliable pressure recovery curve processing methods is an urgent task.

To this end, the generalization of the geological and physical data was conducted, which allows combining fields into separate groups for the subsequent development of recommendations for selecting the type of data processing at the hydrodynamic studies of wells (Table 1).

The main horizons developed on fields of oil-and-gas production department "Yamashneft" were considered. The group is made separately for each reservoir with respect to the type of porosity, properties and composition of cement and lithological characteristics of the reservoir. Ranges of porosity and permeability values are also specified, affecting the quality of the interpretation of the level build-up curves.

Clastic reservoirs and deposits of Bobrikovian and Tulskian horizons of the Lower Carboniferous are of high capacity and highly permeable. All over the productive section the reservoir type is porous. Average permeability range – 220...850x$10^{-3}$ mm2. Cement type is mostly contact, less porous. Cement is slightly developed, of quartz composition, distributed in the form of regeneration rims on detrital grains.

Group of fields from Tulskian-Bobrikovian are presented with three types of rocks: sandstones, mudstones, siltstones.

Productive formations are mainly characterized by the unevenness of the section and heterogeneity.

Carbonate rocks of Bashkirian age are represented mainly by organogenic limestone interbedded with lime dolomite, rarely chemogenic (fine-medium-grained) limestone. In addition to limestone Bashkirian section is marked with inequigranular dolomites often fractured. The cracks are of up to 20 microns.

Reservoirs of Vereiskian horizon are represented mainly by limestone organogenic-clastic interbedded with mudstone silty, micaceous, with thin layers of sandstones grained, calcareous. The middle part of the horizon is composed of carbonate-clastic rocks. Organogenic limestones Tare widely developed in the section of Vereiskian layers.

From Table 1 it is clear that Tyuteevsky, Sirenevsky, Berezovsky, Shegurchinsky, Ekaterinovsky fields have the general geological and physical properties in clastic reservoirs, while their similarity is much less in the carbonate section.

During the hydrodynamic studies and interpretation of the data we must take into account the structure of the investigated formation, especially the pore space, geological and physical characteristics that will keep the correct calculation of reservoir properties.

The present compilation of deposits was held with the aim of developing methodologies for research for each group and selecting the optimal method of results processing. Thus, the grouping of objects by the parameters represented in the table (lithological reservoir characterization, properties and composition of cement, type of porosity, permeability range, porosity range) causes a single, but a qualitative approach to how to conduct well testing and interpreting of the results.

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# Geological Background of the Further Exploration of Oil in the Nizhnekamsk Deflection

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Abstract. On the basis of new geological and geophysical data acquired in recent years, the Institute of Ecology and Natural Resources of the Academy of Sciences of the Republic of Tatarstan conducted studies to clarify the geological structure of Nizhnekamsk deflection of Kama-Kinel system in order to evaluate the oil potential. The article discusses the main features of geological and tectonic evolution and genesis of Nizhnekamsk deflection, which are crucial in clarifying the morphogenetic types of local uplifts and establishing their spatial distribution in the deflection. The question of the share of tectonic and sedimentary processes is considered in the formation of reservoirs and traps in the axial and marginal parts of Nizhnekamsk deflection; the prospects are justified of oil-bearing sediments involved in its structure.

**Keywords**: intraformational deflection, genesis, board, marginal and axial zones, swell, swell-like areas, bioherm, reef, deposit, field.

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Prospects for further search of hydrocarbons in Nizhnekamsk trough of Kama-Kinel System on a background of more effective training areas of oil reserves in the Republic of Tatarstan is far from being exhausted, and allow us to consider this territory as relevant to the preparation of industrial oil, indicating the need for the development of its undiscovered resources.

Within Nizhnekamsk deflection numerous commercial accumulations of oil are established. However, the main deposits are confined to the Devonian clastic rocks, sediments of which are not involved in the construction of Nizhnekamsk deflection. Established Upper Devonian and the Lower Carboniferous carbonate deposits are confined mainly to the board zones and near-board zones of the deflection.

Within the same axial deflection zone from 12 fields discovered only in seven oil deposits are established in carbonate Upper Devonian and carbonate-clastic Upper Carboniferous sediments. Of these, deposits of three fields (Elabuzhsky, Lugovoy, Omarsky) are located within the transition zone from the board to the center – near-board part of the deflection, causing that deposits are confined to the reef structure, common in the board areas of the deflection. Thus, the axis of the imposed intraformational Nizhnekamsk deposit against its sides is characterized by a small number of identified oil deposits.

Nizhnekamsk deflection, which is part of the Kama-Kinel system, is located in the northern part of the Republic of Tatarstan and divides South-Tatar and North-Tatar arches. Nizhnekamsk deflection is independent structure of the first order. Deflection length is about 140 km. The width of the deflection varies from 7-22 km in the west and up to 30-40 km in the east. Nizhnekamsk deflection connects the western part of it, with the same Mozhginsky, Ust-Cheremshansky and, in the eastern part, with Aktanysh-Chishminsky and Sarapulsky deflections (Fig. 1).

History of geological and tectonic evolution and origin of the Nizhnekamsk deflection, as well as the entire Kama-Kinel system is inextricably linked with the early period of formation of the Paleozoic sedimentary rocks of this area and covers a relatively short period of time. In accordance with the selected lithologic and stratigraphic rock complexes that period of time is divided into four stages: Middle Frasnian-Famennian, Tournaisian, Kosvinskian and Radaevskian-Bobrikovian.

Within Nizhnekamsk deflection in pre-Sargaevskian deflection North-Tatar arch held the highest structural position, limited to the south from the South-Tatar arch by largest Prikamsky sublatitudinal fault. Decrease in organic residues for all groups of fauna indicates about the high structural position of the North-Tatar arch. There are no algae, foraminifera, different types of ostracods are increasing (Khisamov et al., 2010).

In the Middle Frasnian time the entire territory in the area of Nizhnekamsk deflection experienced subsidence, which led to a deepening of the marine basin. This tectonic subsidence was performed unevenly, and the result was, as in Lower Frasnian time, the highest structural position of the North-Tatar arch. The relatively high structural position in the bottom of the Middle Frasnian basin of the North-Tatar arch is due to the development in Semilukskian time of organogenic-detrital limestones with remains of ostracods, amfipor and tentaculites, etc. Rechytskian deposits are composed of light-gray and gray massive reef limestone, filled with remnants of algae, stromatopore, amphipore colonies (Khisamov et al., 2010).

The lithological-paleontological characteristic of the Middle Frasnian sediments indicates of very shallow water conditions of their accumulation on the bottom of Middle Frasnian sea.

The area corresponding to the South Tatar arch, occupies an intermediate structural position, being lowered with respect to the North-Tatar arch and raised with respect to restricting it to the west, north and east of depression, within which relatively deep bituminous silica-clay-carbonate rocks were commonly deposited.

Thus, by the end of Rechitskian time structurally this area already had South and North-Tatar paleo-swells and Prikamsky paleo-depression delimiting them. Slopes of paleo-swells, representing a system of flat terraces and steps, located above the fault zones in the crystalline basement rocks, were matched with the board of Prikamsky paleo-depression, within which from Upper Frasnian time Nizhnekamsk deflection of Kama-Kinel system began to form.

In Early Frasnian and Famennian time the amplitude of general tectonic subsidences in the Volga-Ural region has been much greater than in Middle Frasnian age. In terms of tectonic movements regime inherited from the Middle Frasnian time, subsidence was done with different intensities.

The differentiated nature of the tectonic subsidence was captured in the lithological composition and thickness of the Upper Frasnian and Famennian sediments accumulated in dramatically different and separated structural-facies zones. In contrast to the vertices, slopes of paleo-swells were sagged more intensely and in particular their edge zones, which have accumulated 300-500 m thick carbonate strata, mainly of reef rocks. Sustained mode of tectonic subsidence in conjunction with the shallow conditions of sedimentation and wide development in the basin of reef-building organisms (crinoids, foraminifera, algae, etc.) have created optimal conditions for the emergence in the edge zones of structural paleo-swells over structural stages of high-amplitude reef structures.

It should be noted that within the context of common subsidence, area of the northern slope of the South Tatar paleo-depression most intensively expanded, and subsidence rate of the south-eastern slope of the North-Tatar was more intense. This probably explains the displacement of the deflection bed to the north relatively to Prikamsky fault (Fig. 2).

In paleo-depressions in Upper Frasnian-Famennian time rate of tectonic subsidence rate was narrowly ahead of the subsidence rate of edge zones in paleo-swell slopes, and there a deep-water environment of sedimentation remained. At this tectonic-sedimentary environment, bituminous, silica-clay-carbonate sediments of Domanic type continued to accumulate, drastically different in lithofacies, thickness of which did not exceed 140-230 m.

If it is assumed that the amplitude of general tectonic subsidence in paleo-depressions of the Upper Devonian

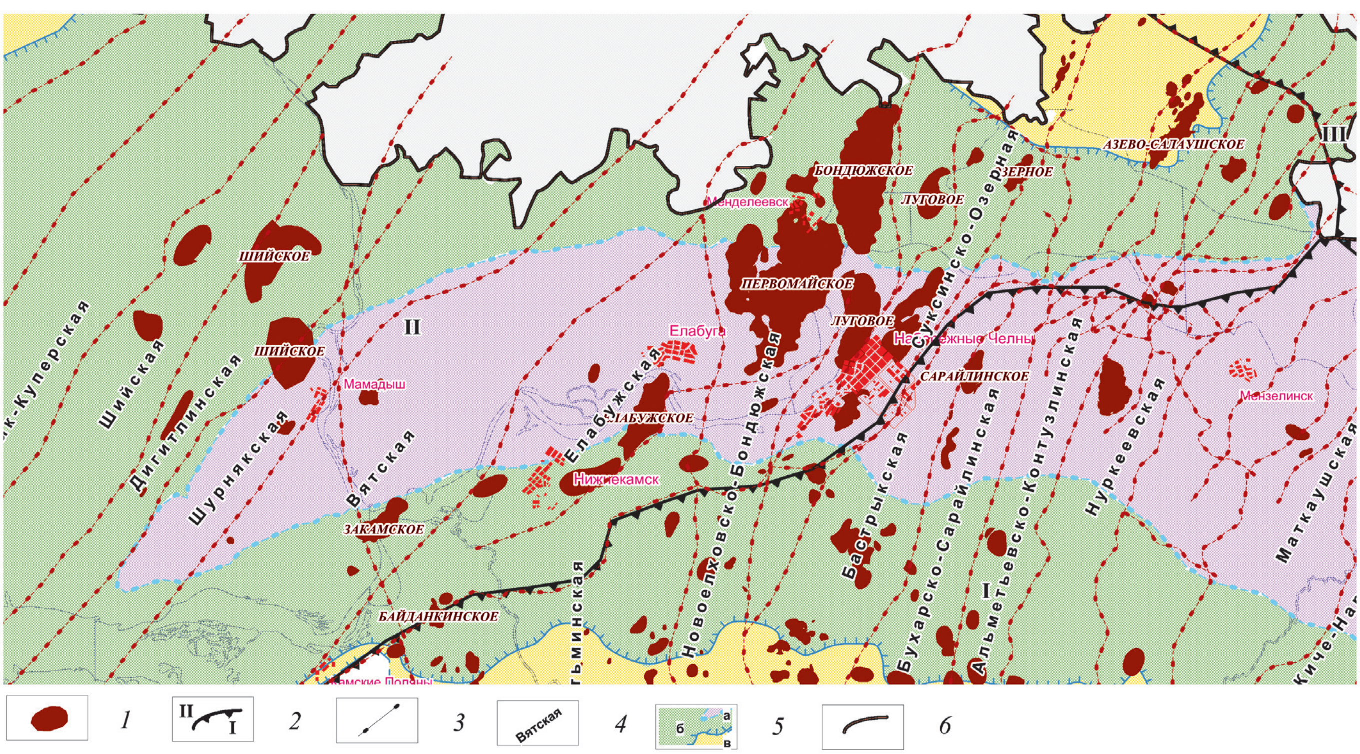


*Fig. 1. Tectonic scheme of Nizhnekamsk deflection circuit with oil-bearing elements (according to Larochkina I.A. with amendments). 1 –oil fields, 2 – modern borders of the I order structures: I – South-Tatar arch, II – North-Tatar arch, III – Kama-Belsky aulacogene, 3 – axial lines of faults, 4 – ridge of the crystalline basement, 5 – zone boundaries of Nizhnekamsk deflection of Kama-Kinel system: a – axis, b – near-board, c-board, 6 – boundary of Tatarstan*

basin was the same as that in the edge zones of paleo-swells (inward deflection of the board), the comparison of its size (180-290 m) with a thickness of 140-230 meters of accumulated sediments here clearly indicates on slippage of sediment accumulation rate from the rate of tectonic subsidence. This non-compensation of tectonic subsidence by sedimentation led to further deepen of paleo-depression originated in Middle-Frasnian time.

With the deepening of paleo-depression and as a result of a significant increase in the amplitude, deflection boards were even more sharply delineated. In the structurally highest parts of boards, developed in depression silica-clay-carbonate rock of Domanic were replaced by coeval carbonate, mainly reef rocks of the edge zones of paleo-swell slopes. This substitution occurs in a narrow band with width of 1.5-3 km and is accompanied by a sharp increase in Upper Frasnian -Famennian deposits. As a consequence, ledges with a height of 150-250 m occurred in the indicated band. Within ledges layers occurring in the roof of Famennian stage are inclined to the central portions of the depressions and have steep angles of incidence (up to 10-15°).

A feature of Tournasian stage of geological history is that its onset began with filling sediments from previously arisen deflection (Fig. 3, 4). Thickness of Tournaisian deepwater sediments of the defleiction is 35-155 m. Given the same lowering amplitude in paleo-depressions and areas of paleo-swells in Tournasian basin, which is 80-230 m, it is possible to conclude about a significant lag in the rate of sediments accumulation in paleo-depression from the speed of tectonic subsidence.

In the axial part of the deflection in the first half of the Tournasian stage deep-sea sediments were throughout deposited. In Malevskian-Upinskian time in the central axial part of the basin the most deep-sea sediments were accumulated. Their composition is dominated by bituminous siliceous-argillaceous limestone, shale, marl, often interlayered with silicified argillites. The thickness of this complex, similar to their underlying Devonian deposits of Domanic facies, is 15-55 m.

In the northern near-board zone of deflection the thickness of siliceous-carbonate, carbonate-clay and clay-carbonate Malevskian-Upinskian deposits, also deposited in the deep-water (but less than in the central part of the basin) conditions, is 15-55 m; in the southern near-board area the thickness is 20-130 m. The difference between the amplitude (5-55 m) of tectonic subsidence and said thickness in the southern near-board deflection zone indicates that in Malevskian-Upinskian time sedimentation rate is slightly higher than the rate of subsidence. Naturally, such a direction of sedimentation contributed to the gradual equalization of Nizhnekamsk deflection profile.

Geomorphological alignment of deflection primarily covered band directly adjacent to the wings of Upper Devonian – Zavolzhskian reefs, i.e. near-board deflection zones, and did not affect its central parts.

In Cherepetskian-Kizelovskian time geomorphological alignment of Nizhnekamsk deflection began to develop even more. During this time, within the paleo-swells and central deflection part structure-depositional facies conditions have not changed substantially. In the central

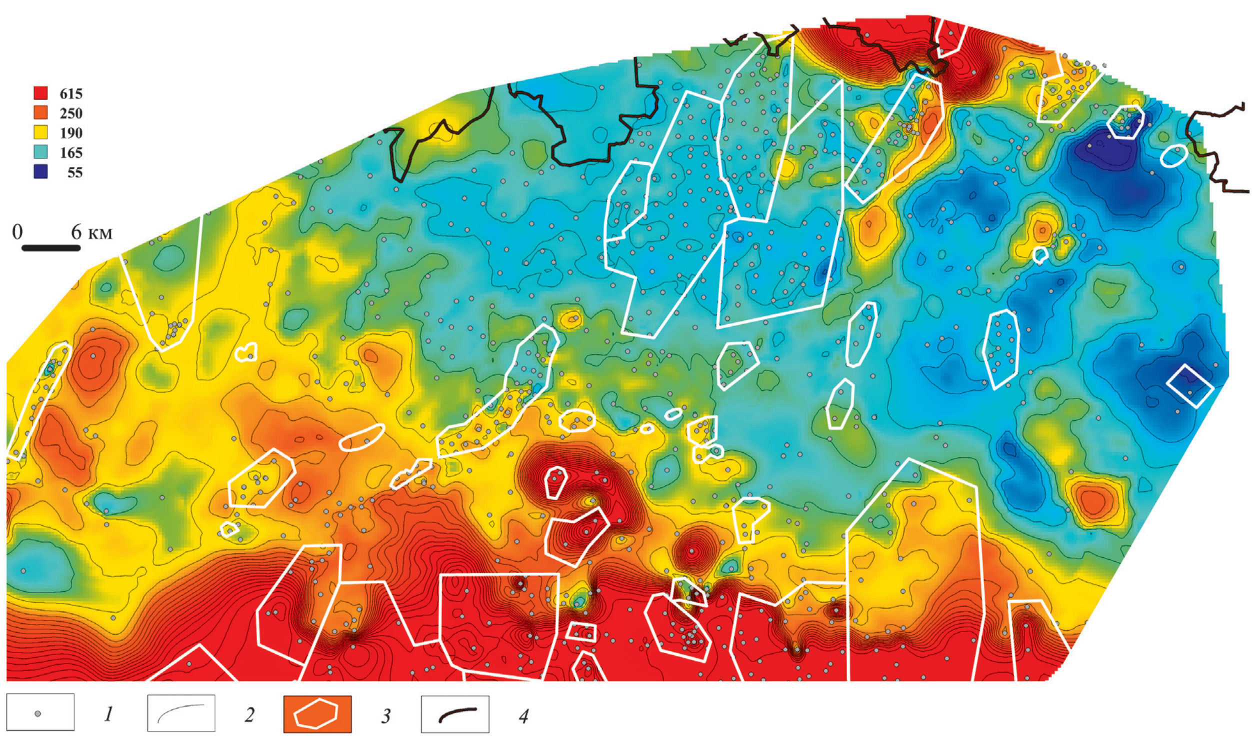


*Fig. 2. Thickness map of deposits of Semshukskian-Zavolzhskian complex. 1 – deep drilling wells, 2 – isopachs, 3 – licensing borders of oil fields, 4 – boundary of Tatarstan*

part of the basin deep siliceous-clay-carbonate rocks of Domanic were still accumulating.

Thickness of Cherepetskian-Kizelovskian rocks deposited within the central part of the basin, is on average 10-125 m, corresponding to the amplitude of common tectonic subsidence throughout the territory. In near-board zones of deflections in Cherepetskian-Kizelovskian time thickness of the carbonate and clay-carbonate rocks accumulated with thickness of 75-245 m – on the north and 135-290 m – at the southern near-board zone.

In the initial period of this sedimentary sub-step of Tournasian time sediments were deposited that carry features of relatively deep, but as near-board zones of trough were compensated and relief of basin bottom was smoothed, and, consequently, the area was reduced that was occupied by the most deep-water part of the sea; shallow marine, mainly organogenic limestones were

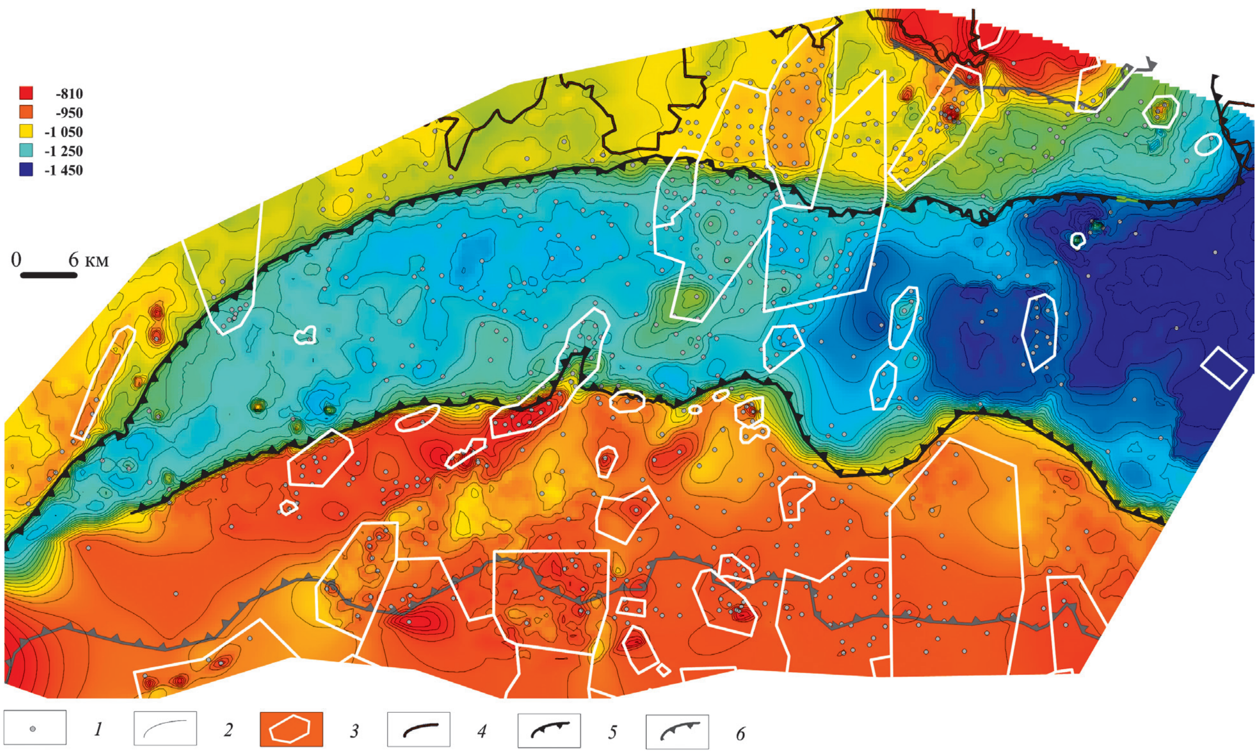


*Fig. 3. Structure map of the Tournasian surface. 1 – deep drilling wells, 2 – isopachs, 3- licensing borders of oil fields, 4 – boundary of Tatarstan, zone boundaries of Nizhnekamsk deflection of Kama-Kinel system; 5 – axial, 6 – board*

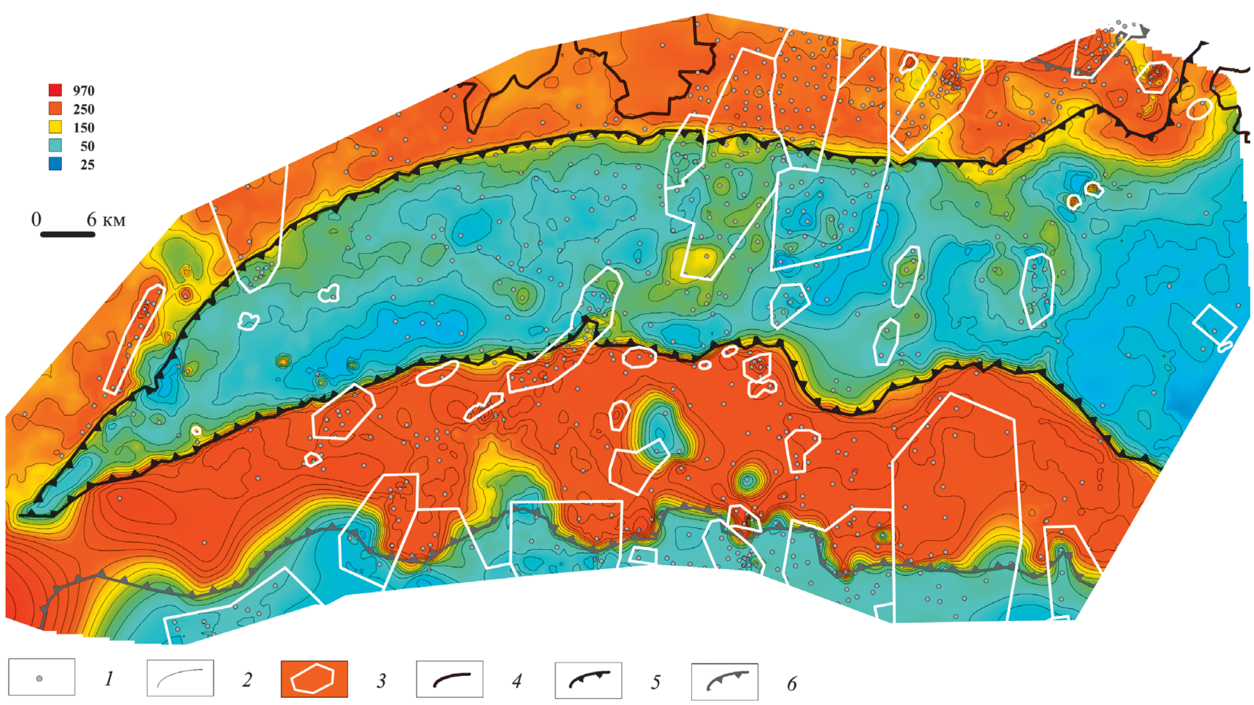


*Fig. 4. Thickness map of the Tournasian sediments. 1 – deep drilling wells, 2 – isopachs, 3- licensing borders of oil fields, 4 – boundary of Tatarstan, zone boundaries of Nizhnekamsk deflection of Kama-Kinel system; 5 – axial, 6 – board*

accumulated, as well as individual packs and interlayers of mudstone, often silicified.

Among organogenous, often clot-biomorphic limestone, the following are present – coral, brachiopod, crinoid-algal, algal-foraminiferal differences found in certain facial proportions with clay limestone. In general, in near-board areas of deflection due to a small amplitude of common tectonic subsidence, quite large reef constructions occurred in size, but low-amplitude (15-25 m) – biostromes and bioherms. The most optimal conditions for the development of Cherepetskian-Kizelovskian bioherm were in the band, immediately adjacent to the boundary of shallow biogenic limestones and relatively deep siliceous-clay-carbonate rocks and shales.

In addition, in near-board and axial areas on the already formed in Late Frasnian-Famennian time geomorphologically pronounced high-amplitude elevations, which gave the beginning of the formation of reef structures, there were small in area high-amplitude reefs. Ozerny, North-Ozevrny, South-Ozerny, Smolny and others can be attributed to such reefs.

As a result of deflection filling, further migration of reef facies is observed of deep troughs in their near-board zone where small-amplitude bioherms and sedimentogene uplifts – reefs occurred.

Thus, the end result of geomorphological analyzed Malevskian-Kizelovskian stage is expressed in a considerable compensation by mainly calcareous, clay-carbonate and carbonate-argillic strata in near-board parts of deflection. Filling of deflection accompanied by simultaneous growth of the territory occupied by shallow-marine facies, seized the second half of Malevskian-Kizelovskian stage and their near-board zones. By the end of Tournasian stage the band occupied by deepwater facies significantly (2-3 times) narrowed, occupying the central part of the deflection and having uncompensated Malevskian-Kizelovskian accumulations.

In Kosvinskian stage of geologic history the geomorphological alignment process, which began in Tournasian time with near-board areas captured central, or axial zones of Nizhnekamsk deflection of the Kama-Kinel system (Fig. 5). From Kosvinskian time, when the general rise throughout the territory clearly outlined, regressive cycle came of Tournasian sedimentation phase, when approaching the sources ablation on the platform, clastic material was brought in a huge amount. On the background of common regressive sedimentation conditions in the swells in Kosvinskian time shallow marine deposits were accumulated, usually made of 3-5 m of mudstone. Here, as a rule, presented Kosvinskian layers are stratigraphically incomplete due to breaks and washouts, upper layers of sections are absent.

In near-board areas of deflection in relatively shallow (but deeper than in swells) conditions there are also stratigraphically incomplete strata of primarily clay sediments, with a thickness of 5-100 m. In the axial part of the basin, which is a relief in the bottom of the basin with the depth of 70-265 m, thick strata mainly of clay accumulated.

The presence of spikula limestone and cephalopod fauna, the amount of which decreases from the base to the roof of Kosvinskian deposits, the prevalence of finely

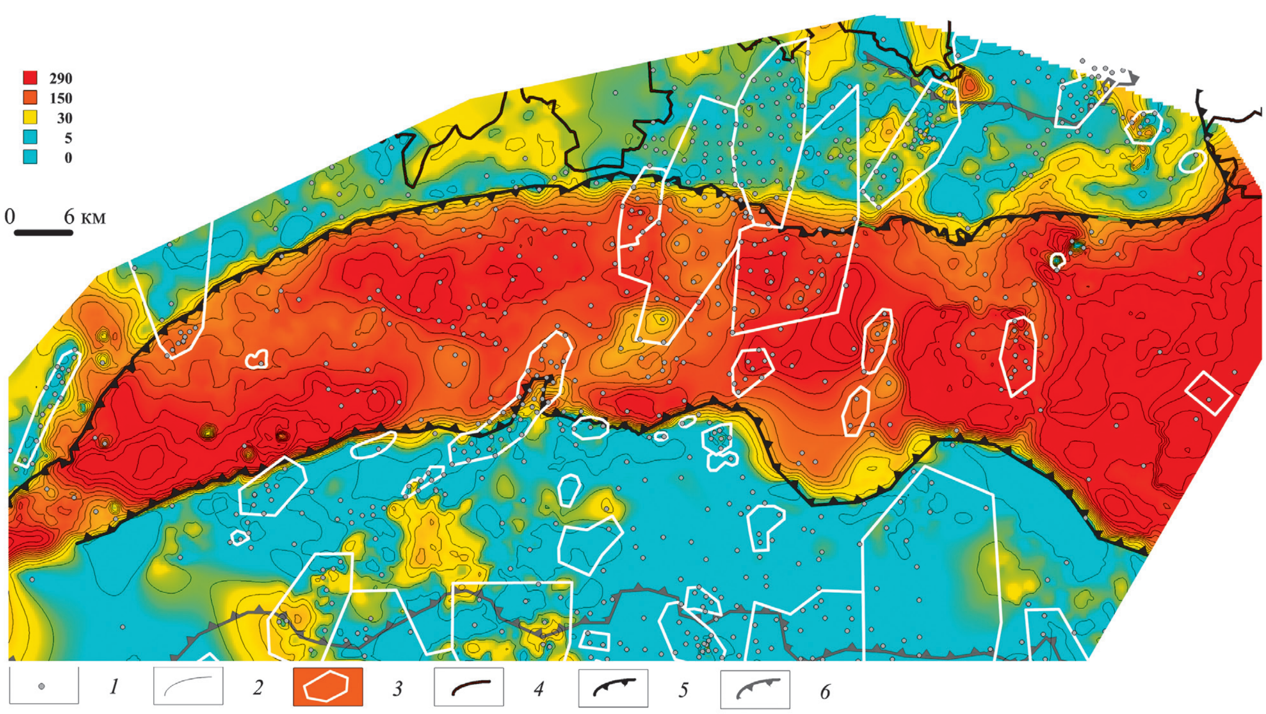


*Fig. 5. Thickness map of the Kosvinskian sediments. 1 – deep drilling wells, 2 – isopachs, 3- licensing borders of oil fields, 4 – boundary of Tatarstan, zone boundaries of Nizhnekamsk deflection of Kama-Kinel system; 5 – axial, 6 – board*

sculpted forms in the fauna of brachiopods, combined with textural features of mudstone suggests that they were formed in relatively deep water conditions. Mudstones deposited in the central parts of the deflection directly on the deep siliceous-argillaceous limestone of Kizelovskian horizon, which is consistent with the conclusion about the presence of deep depression in the bottom of Kosvinskian basin.

Due to mechanical differentiation of sediments, the copious amounts of clay material entered in the depression in the first place. The rate of admission of this material is many times faster than common tectonic subsidence, which promoted the accumulation of 70-210 meters strata of argillaceous rocks. Such sedimentation regime led to the end of Kosvinskian stage the central part of deflection was loaded with clay, substantially aligned their profile.

Radaevskian-Bobrikovian stage of geological history of the Kama-Kinel system did not occur in marine, but continental sedimentary environment, qualitatively different from those of the previous stages (Fig. 6). In Radaevskian-Bobrikovian time there was a system of large and small brackish waters with a wide network of islands.

In the territories occupied in Radaevskian time by board and near-board deflection zones, a break in sedimentation is recorded, accompanied by partial or total erosion of the underlying Kosvinskian sediments. In the axial part of the basin, which represented in relief broad, shallow depression, the largest body of water was located. In this reservoir sedimentation process was not interrupted, and bog-lake and alluvial formations were deposited. Sand-siltstone and carbonaceous-clay composition and textural-structural features (cross-bedding of sand and silty rocks, traces of plant root systems, etc.) of these formations show very shallow conditions of their burial.

The accumulation of sediments in these parts of the deflection, limited by denudation areas, was done not in a sea basin, but in a coastal plain, within which only occasionally and briefly seawater penetrated. The character of areal development of Radaevskian horizon indicates that in the initial stages of sedimentation ponds were small, and it occupied the most loaded zones of preserved depressions – the central part of the Nizhnekamsk deflection.

With the accumulation of sediment, borders of this shoaling reservoir widened, and it has spread within the near-board zone along the central part of the basin. All this gives grounds to assume that the axial zone of Nizhnekamsk deflection loaded with Radayevskian deposits, with thickness of up to 150 m, wedging to near-board zones, mainly in the southern near-board zone.

The overlying Bobrikovian deposits were accumulated in a relatively leveled terrain of coastal continental lowlands. Bobrikovian deposits occurring in near-board areas with erosion and stratigraphic unconformity, in the studied area are developed everywhere. Extensive development of Bobrikovian deposits is connected to the subsidence throughout the territory of the Volga-Ural region, marking the advent of more common and stable tectonic subsidence, which caused a new transgression of the sea basin.

If the total amplitude of frequent tectonic subsidence in the area is 10-30 m, in Radaevskian-Bobrikovian stage in the central remained unloaded parts sediments

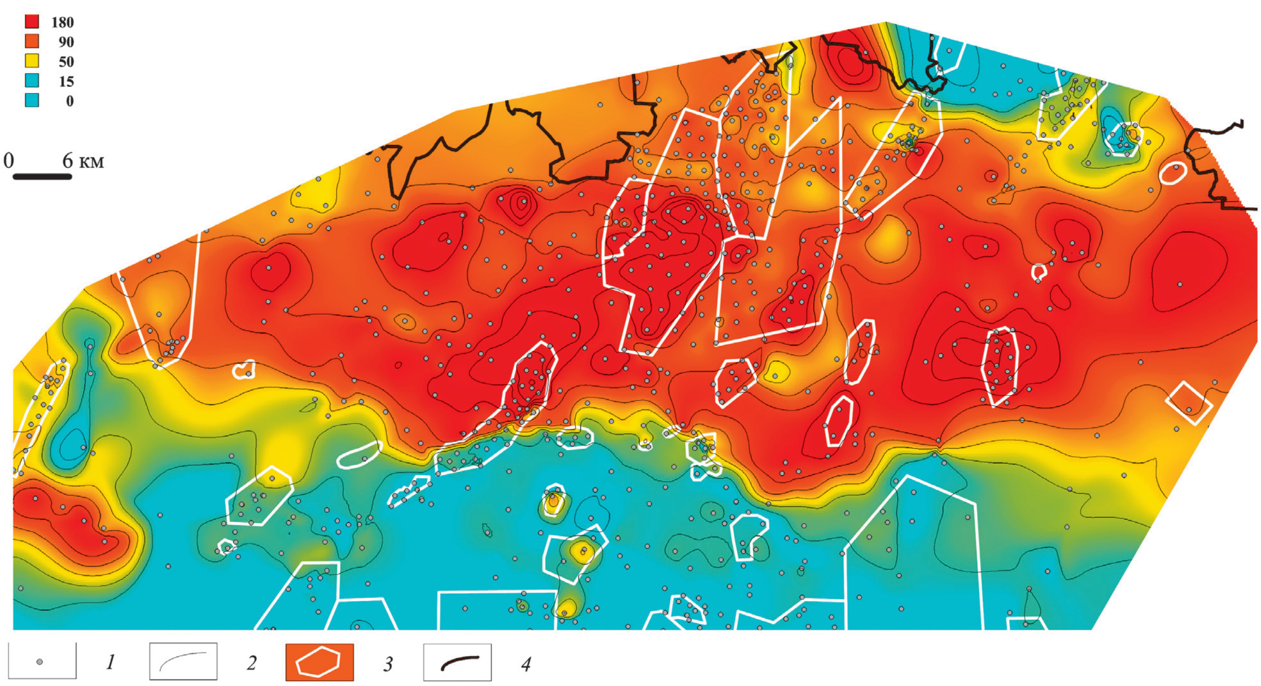


*Fig. 6. Thickness map of the Radayevskian-Bobrikovian sediments. 1 – deep drilling wells, 2 – isopachs, 3- licensing borders of oil fields, 4 – boundary of Tatarstan*

of 50-150 m were accumulated. During this phase, high sedimentation rate still remained compared with the tectonic subsidence, which provided deflection filling. By the beginning of Tulskian time Nizhnekamsk deflection, not completely, but geomorphologically was aligned.

In post-Bobrikovian time Nizhnekamsk deflection has ceased to develop under a single, general plan. In Tulskian time with the onset of sea transgression a new stage of geologic history begins.

Upon consideration of the main features of geological and tectonic evolution and genesis of Nizhnekamsk deflection we can draw the following conclusions.

1. Tectonic stratification of the territory in the South and the North Tatar paleo-arches and the Kama paleo-depression caused by the end of the Middle Frasnian time separation of structural-facial zones and prepared the necessary conditions for the formation of Nizhnekamsk deflection.

2. Along with the region-wide irregular tectonic subsidence in the formation of the deflection significant role belonged to the sedimentation characteristics, expressed in uncompensated sedimentation of paleo-depression; Nizhnekamsk deflection is formed in Upper Frasnian-Zavolzhskian time.

3. In the marginal zones of paleo-arches reef barrier-type structures arose; the development of top-Frasnian-Volga reef structures are genetically related to the formation of these depressions.

4. Carbonate, clay-carbonate and carbonate-clay Tournaisian sediments compensated near-board zones of deflection. The process of filling depressions was accompanied by development in near-board areas of low amplitude bioherms and biostromes. Kosvinskian and Radaevskian-Bobrikovian clastic deposits compensate the most loaded deflection zones.

By the nature of relations with the underlying and overlying sediments Nizhnekamsk deflection is not reflected. The axial deflection zone is shifted northward relative to the axis of Kama fault on the underlying sediments. Geographically Nizhnekamsk deflection is located in the south-eastern slope of the North-Tatar arch.

Axis misalignment of the deflection is caused by younger, mostly late and post Permian tectonic uplifts of the northern near-board area, where a system of swells was formed (Pervomaysko-Bondyuzhsky, Yelabugzhsky, Suksinsko-Ozerny, etc.), and lowerings of the southern near-board area. This partial restructuring has led to the fact that in the present structural plan over the deepest central part of the Kama fault is located in the main southern near-board zone of Nizhnekamsk deflection. Nizhnekamsk deflection in the Devonian clastic strata corresponds to monoclinal bedding of layers.

The main provisions stemming from the structural features of the Upper and Lower Carboniferous sediments and history of geotectonic development of Nizhnekamsk deflection are initial and in many ways decisive in clarifying the morphogenetic types of local uplifts and establishing their spatial distribution in the deflection and associated with them edge zones of arches.

Within Nizhnekamsk deflection swells are developed, the long axes of which are oriented to the northeast and cut structural elements of Nizhnekamsk deflection (intersecting swells). Intersecting swells of the northeast strike repeat the main features of the structural-tectonic plan of Devonian formations. Swell-like zones of Devonian deposits, in turn, reflect the picture of the crystalline basement surface, forming a system of ridges (Fig. 1) of the same stretch: Shurnyaksky, Vyatsky, Yelabuzhsky, Novo-Elkhovsky, Bondyuzhsky, Suksinsko-Ozerny, Bukharsko-Saraylinsky etc. (Larochkina, 2013). General feature for intersecting swells is that participation of tectonic factor is required in the formation of the constituent local uplifts.

Located on intersecting swells local uplifts are confined to various structural-facies zones of Nizhnekamsk deflection, characterizing depending on which zone they are located, well defined by structural relations for various age horizons. Thus, these swells are generally at a sufficient extent combine local uplifts of various morphogenetic types.

Local uplifts, owing their origin to tectonic factor (without bioherms of Upper Frasnian-Zavolzhskian and Malevskian-Kizelovskian age), are confined to swells, which are geographically located in the axial and northern near-board areas of Nizhnekamsk deflection (Bondyuzhsky, Pervomaisky, Lugovoy, Saraylinsky et al.)

Unfortunately, swell-like structures are not expected, developed on the boards of the Nizhnekamsk deflection and owing their formation and genesis to sedimentation factor (analog to Arlansky). Sedimentation is the predominant factor for the southern board zone (Svinogorsky, Novo-Suksinsky, Zychebashevsky, Elginsky, Vinokurovsky, Urgundinsky, Abdulovsky and other uplifts), but tectonic factor plays an important role. Genesis of swell-like structures of the southern board is tectonic-sedimentation. Such uplifts are formed mainly due to structure forming ability of reef facies of Famennian-Zavolzhskian and-Malevskian-Kizelovskian deposits with the subordinate role of tectonic factors.

Special structures are attributed to sedimentation-tectonic uplifts, in the formation of which tectonic factor was manifested many times, and prevailed, and sedimentation factor led to the emergence of relatively low (a few tens of meters) bioherms (Mamadyshsky and others). These uplifts are clearly expressed in the sediments underlying the bioherms, in particular layers of Devonian clastic strata, in which the amplitude is greater than for the Upper Carboniferous deposits.

An important feature of most of the uplifts of this type is the displacement of the dome portion on the roof of the Famennian-Zavolzhskian and younger sediments toward the steep wing and regional tilt of layers and can often serve as an indicator of simultaneous action of tectonic and sedimentary factors, in which bioherm in the process of its growth constantly attempted to be above the band of accelerated and sustainable dipping of seabed.

Bioherms of Rechtskian-Danskian-Levedyanskian and Malevskian-Kizelovskian ages are attributed to the structure forming carbonate reef (biohermal) arrays, genetically related to Nizhnekamsk deflection. Urazbahtinsky, Omarsky, Smolny, Shirmansky, Demyanovsky, Ozerny, North-Ozerny, Prirazlomny, West-Yurtovsky, Timerovsky and Otarny uplifts are attributed to the above-mentioned uplifts with biohers in the core in the form of single structures. All single high-amplitude structures – reefs are confined to axial and internal near-board deflection zones. From mentioned uplifts only Omarsky has proven sedimentation genesis, the other uplifts are tectonic-sedimentation.

It is important to emphasize that local uplifts, the structural relations of which are due to the participation of Upper Frasnian-Famennian and Malevskian-Kizelovskian bioherms, genetically closely related to the Nizhnekamsk deflection.

Thus, in the axial zones of troughs only tectonic uplifts and sedimentation and tectonic single reefs are developed. In near-board areas along with sedimentation and tectonic uplifts also tectonic-sedimentary and sedimentary uplifts are developed with Malevskian-Kizelovskian and rarely Famennian-Zavolzhskian bioherms.

Analysis of the geological development, structure, and established laws of placing deposits allows linking the prospects for further search of oil in Nizhnekamsk deflection with the following three types of traps: tectonic uplifts, Middle Frasnian- Kizelovskian reef constructions, areas of structural and lithologic traps. The potential for the spread of the combined traps is obvious: sedimentary-tectonic – and lithologic –stratigraphic – in near-board areas.

Let us note that in the fields of Nizhnekamsk deflection, the main productive horizons are mainly deposits covering the reef arrays (Ozerny, Lugovoy, Bakhchisaraisky, Biklyansky and others). Deposits directly in the reef rocks are rare and controlled mainly by single high amplitude biohermal sturctures (Menzelinsky, Timerovsky, etc.). In such fields sand-siltstone rocks of the Lower Carboniferous clastic strata are favorable for the accumulation of oil and gas reservoirs; in the case of the Upper Devonian-Zavolzhskian or Upper Tournaisian reef masses – carbonate rocks that form these arrays.

Traps of tectonic type account for the vast majority of projected by seismic survey for further searches and established oil and gas structures. Given the stable block structure of the crystalline basement (ridge), in the western part of the deflection, in contrast to the central, where there are mainly large deposits of oil, due to the weak differentiation large extended and sharply expressed contrasting uplifts are not expected.

At the same time, the probability of detection of new medium- and small-amplitude elevations, especially taking into account the favorable tectonic conditions of their formation at the joints of structural terraces, along the basement faults, is very high. Identification of tectonic traps is expected in the eastern parts of the deflection.

Axial deflection zone is characterized by the presence of structural traps in the form of tectonic uplifts, which at sufficiently high amplitude may appear very promising. Oil deposits may have sand and silt reservoirs of Carboniferous clastic strata, and in some cases, fractured, sometimes porous-cavernous carbonate rocks of the Upper Devonian, Tournasian, Bashkirian and Moscovian ages.

In the axial zone of the deflection within the tectonic and sedimentary-tectonic structures Upper Frasnian-Kizelovskian rocks of Domanic facies may serve as reservoirs in the event of strong fracturing and sufficient permeability. Domanic facies of carbonate stratum of the Upper Devonian, forming the bed deflection, are regionally bituminous. Signs of oil content in the form of spotted oil saturation and inclusions of tarred viscous oil were observed in the core during the drilling of many wells.

Particular attention, in connection with the established unique high-capacity oil traps in Nizhnekamsk deflection should attract high-amplitude single reef sturctures of tectonic-sedimentary origin. The development of long-term trends associated with reef structures is an important reserve for future searches.

The west end of the deflection is the perspective in this direction, where by seismic data a number of uplifts are mapped, and its eastern part in the strike of the Prikamsky fault, expressed in sharply differentiated surface of the basement, in the conjunction of axial and near-board deflection parts (Fig. 1). In addition, the main interest in conducting seismic survey should represent the intersection portions of near-board and board areas with intersecting tectonic dislocations favorable for the formation of contrasting sedimentary-tectonic structures and their systems.

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# Lithological and Petrographic Characteristics of Aleuropelitic Ishimskian Deposits in the Western Part of Tobol-Ishim Interstream Area

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**Abstract.** The lithological and petrographic analysis of aleuropelitic rocks of Ishimskian suite of the Upper Miocene was conducted for outcrops "Bigila", "Pyatkovo" and "Masali" in the south of Tyumen Region. The data obtained complete the previously performed research of material composition, physical properties and identification of preliminary age of the upper part of Ishimskian suite. The results of these studies do not record significant differences in the lithology of the studied species, presented in different exposures: rocks are identical in their mineral composition and structural and textural features, confirming the community of their formation conditions.

The studied rocks are composed mainly of fine poorly rounded quartz; in small quantities contained feldspar and mica. Feldspars consist principally of plagioclase, less microcline, which is confirmed by the determination of rocks chemical composition by X-ray analysis. Micas are present in the form of thin flakes with a bright interference color. Very rarely there are small grains of round glauconite, yellow-green, the exact origin of which is not yet set. In the outcrop Masali aleuropelitic rocks are overlapped by clayey silt with a high content of dispersed organic matter and coalified plant detritus. High dispersion and predominantly quartz composition allows us to characterize the studied rocks as marshallits. In this respect, more detailed studies must be based on analytical and instrumental methods that could be applied for this type of rocks. Persistence of the thickness of deposits over a large area gives grounds to consider the formation of the Ishimskian suite along with other horizons of the Middle Cenozoic as objects for prospecting siliceous raw materials.

**Keywords:** aleuropelites, Ishimian suite, lithology, Tyumen region, marshallit, natural microsilica
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## Introduction

Deposits of Ishimskian suite of Upper Miocene, distributed in the valleys of small rivers in the south of the Tyumen region, are highly informative for the reconstruction of paleogeographic conditions and history of the territory of the Tobol-Ishim interstream in the Neogene. These rocks are generally described as bleached aleuropelites or mealy silts (Astapov et al., 1964), in some studies their resemblance is noted with the Eocene diatomites and tripolis of Trans-Urals (Kuznetsov, 1963).

Despite the importance of stratification in the continental Neogene in Western Siberia and the great potential for paleogeographic reconstructions, deposits of Ishimskian suite in northern areas of its distribution remain poorly studied. Suite stratotype is considered section of Petropavlovsk (Martynov, 1967; 1964; Zykin, 2012). General information on the distribution of the suite within the Tobol-Ishim interstream is contained mainly in the works of A.P. Astapov, relating to the 70-s of the last century (Astapov et al., 1964; 1979; Astapov, 1977).

The results of earlier studies of Ishimskian aleuropelites revealed abnormally high dispersion of these sediments for rocks quartz composition, which allowed characterizing them as marshallites (Smirnov et al., 2016), as well as to confirm that they belong to the Late Miocene (Kuzmin et al., 2016). In this paper we present the results of lithological and petrographic analysis of the Ishimskian suite deposits from three outcrops in the western part of the Tobol-Ishim interstream and their interpretation.

## Objects and methods of investigation

Field studies were carried out on the territory of Zavodoukovsky and Uporovsky districts of the Tyumen region within three key areas – "Bigila", "Masali" and "Pyatkovo" – confined to the eponymous human settlements (Fig. 1). According to the geomorphological zoning of the south of Western Siberia, the area of the field work is located on the Ishim denudation sloping plain (Varlamov, 1972) with altitudes of 50-150 m above sea level (Zemtsov et al., 1988). The area is distinguished by the degree of relief stratification sufficiently high for the south of the Tyumen region: a linear division of ravines, gullies and valleys of the small rivers is 0.6-1.2 (Atlas of the Tyumen Region, 1971). The river network of the studied area belongs to the Kara Sea basin; main river – Tobol. Valleys of small rivers – Bigila, Kizak and Kurchigay – are included into the valleys of the river network of the Neogene.

Within the boundaries of the areas under consideration Ishimskian suite combines layers of assorted sand and bleached tripoli aleuropelitic rocks, considered geologically coherent and unified suite up to 20 m (Fig. 2) (Astapov et al., 1979). The transition from the sandy alluvium to aleuropelites is gradual; bottom contact is usually clear, even with signs of minor areal erosion. In the studied outcrops the presence of basal horizon is recorded, which is composed of coarse-grained, sometimes gravelly sands, with mafic minerals and quartz pebbles, with a scythe, belt, diagonal stratification, with thickness of 5-10 cm.

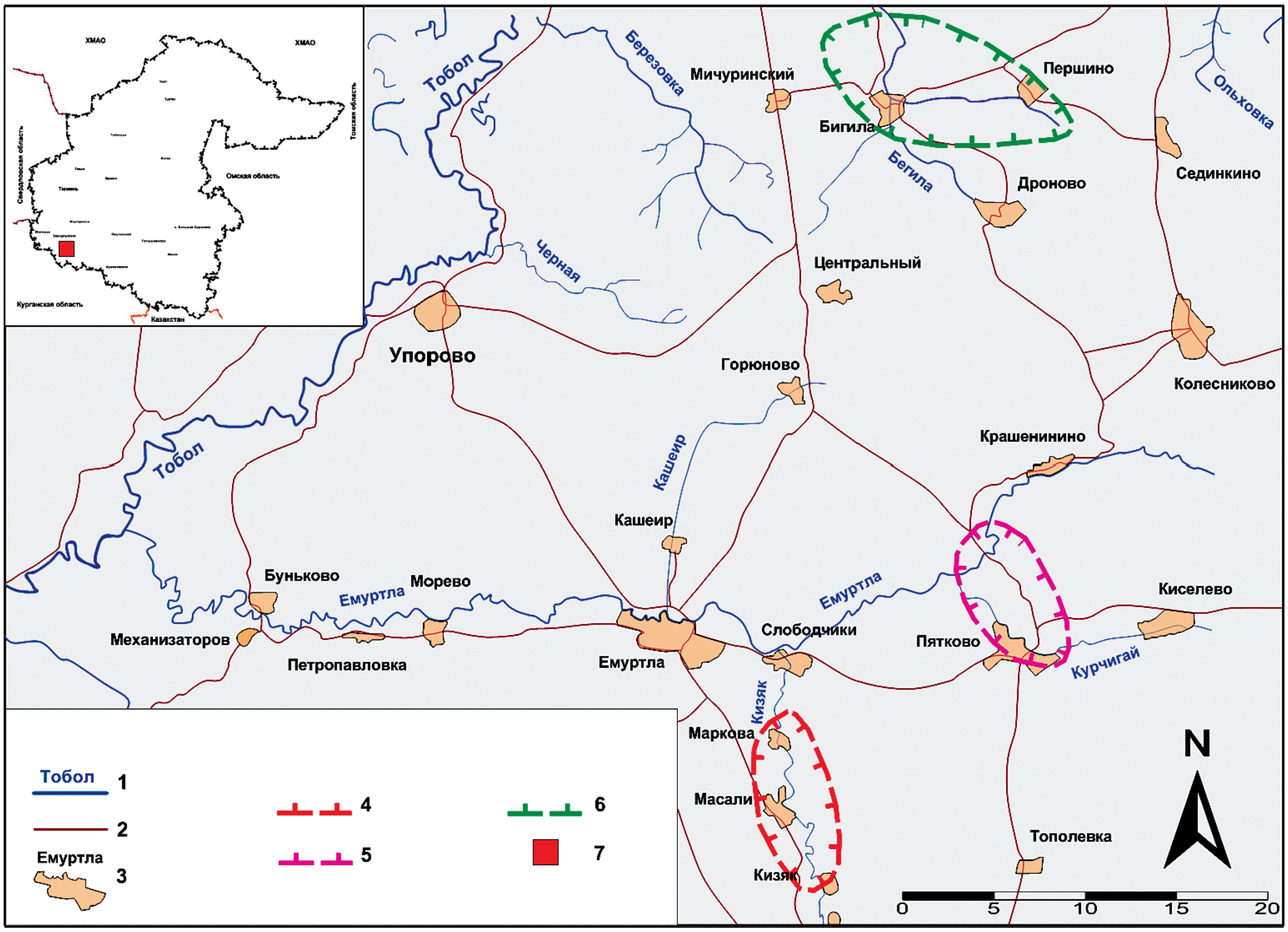


*Fig. 1. Map of the actual material: 1 – river network; 2 – roads; 3 – settlements; 4 – border of key area "Masali", 5 – border of key area "Pyatkovo", 6 – border of key area "Bigila", 7 – location of the research areas within the south of the Tyumen region.*

In outcrops aleuropelitic strata is conventionally divided into two parts: the largely ferruginous lower and upper bleached. Rarely in the lower pack of aleuropelites there are small clusters of black manganese nodules, rod-shaped, nodular, with tuberculate surface.

Previous studies have established (Smirnov et al., 2016) that, in general, the thickness is not uniform in mineral composition laterally and vertically.

The top of the aleuropelitic column is characterized by the largest values of silicone dioxide and the smallest of lithophile element oxides ($Al_2O_3$, $Fe_2O_3$, $TiO_2$, etc.), and accordingly, the higher content of silica and lower content of clay minerals. Aleuropelitic rock has the following mineralogical composition: quartz (61.1-85.6 %), potassium feldspar and microcline (up 6.9 %), acid plagioclase or albite (to 14.2 %) (Smirnov et al., 2016).

The study was carried out in thin sections prepared by the standard method (Shvetsov, 1958).

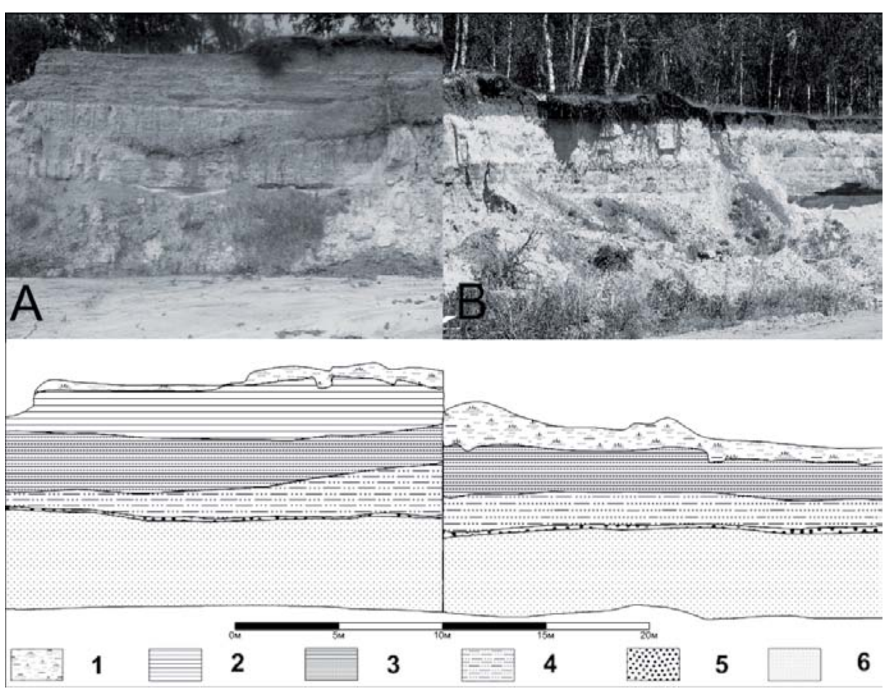


*Fig. 2. Outcrops scheme (sections: A – "Masali", B – "Bigila"); 1 – soil-vegetation layer; 2 – clay and silty rocks overlying aleuropelites of Ishimskian suite; 3 – upper (light) pack of aleuropelitic column; 4 – lower (ferruginous) pack of aleuropelitic column; 5 – basal horizon; b – sands of Ishimskian suite*

## Research results

According to the results of previous studies (Smirnov et al., 2016) loose aleuropelitic rock, presented in a natural outcrop "Bigila" has aleuropilitic structure with particle size of less than 0.01-0.001 mm, individually up to 0.03 mm. Fragments are mainly represented by quartz and the finest scales of hydromica (Fig. 3). There are rounded isolations of up to 0.03 mm, yellowish in parallel Nicols, belonging to mixed layers of formations that are supported by the analysis of chemical composition made by means of X-ray diffraction (Smirnov et al., 2016). Ore minerals are more or less evenly scattered with pyrite impregnation, which is not more than 1 to 2 %, and ore minerals, undetermined due to full leucoxenization (about 5 %). The accessory minerals are presented by titanium with a crystal size of 0.01 mm and constituting 4-5 %.

In outcrop "Masali" apparent thickness of exposed rocks is 4.5 m. At the bottom of outcrops aleuropelites occur light, almost white; aleuropelitic stratum overlaps clay-silty rocks with a high content of sand material and organic matter (Kuzmin et al., 2016). Aleuropelitic rock is light-gray, homogeneous, weakly cemented, flabby, mica, light, when crushed dusty, sticks to the tongue, when interacting with HC1, the reaction is not observed. Rock structure is aleuropelitic, pelitomorphic; texture of rocks is homogeneous (Fig. 4).

The rock consists of 90 % angular quartz grains, the maximum size of which is 0.12 mm, an average particle diameter greater than 0.05 mm, make up 3-5 % of the rock volume, the predominant grain size is 0.005-0.012 mm. In a small number feldspar and mica are contained (mostly highly water sensitive). Feldspars are presented by acidic plagioclase. Hydromica is present in the form of thin flakes with a bright interference color. Small, round, yellow-green glauconite grains are very rare.

In the sample there are round-shaped formations consisting of quartz grains of the same size, of which the rock is composed, cemented by a rather amorphous material, apparently opal/ halcedony. Clay minerals are presented by chlorite scales.

Across the sample there are rather small black grains (size <0.005 mm) scattered, the mineral composition of which cannot be reliably determined in view of their very small size (presumably ore minerals).

Since the rock is weakly cemented, flabby, with a little amount of binder, within 3-5 %, has a point (contact) and pore distribution type, consists of authigenic silica, chlorite and hydromica. Rock sample has a relatively high microporosity (sample rapidly turned into blue), formed by intergranular pores with size of less than 0.005 mm. Moves of burrowing organisms are also met, filled with the larger material. Moves are intensely impregnated with limonite (Fig. 5).

Clay-siltstone rocks overlying aleuropelites, from light gray to dark brown, almost black, are sometimes ferruginized, with a high content of organic material and sand. The rocks are composed of clay minerals, mainly hydromica, with an admixture of debris of sand fraction. Fragments of quartz in fine sand fraction are of size 0.05-0.16 mm; silty impurity is less than 5%. Throughout the presence of dispersed organic matter and coalified plant detritus is recorded.

In "Pyatkovo" section similar in appearance to the first two objects of rock are exposed; the only significant difference is a

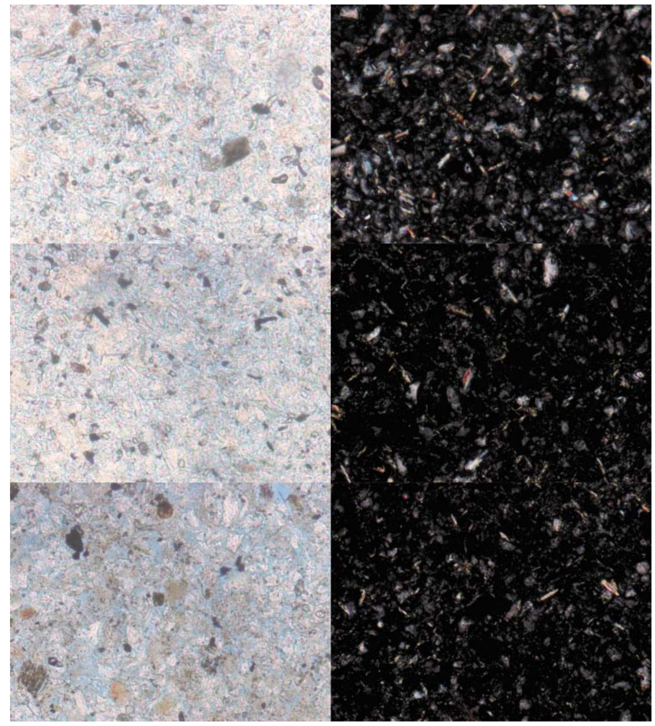

*Fig. 3. General view of the aleuropelitic rock outcrop "Bigila" (left – parallel Nicols, right – crossed Nicols).*

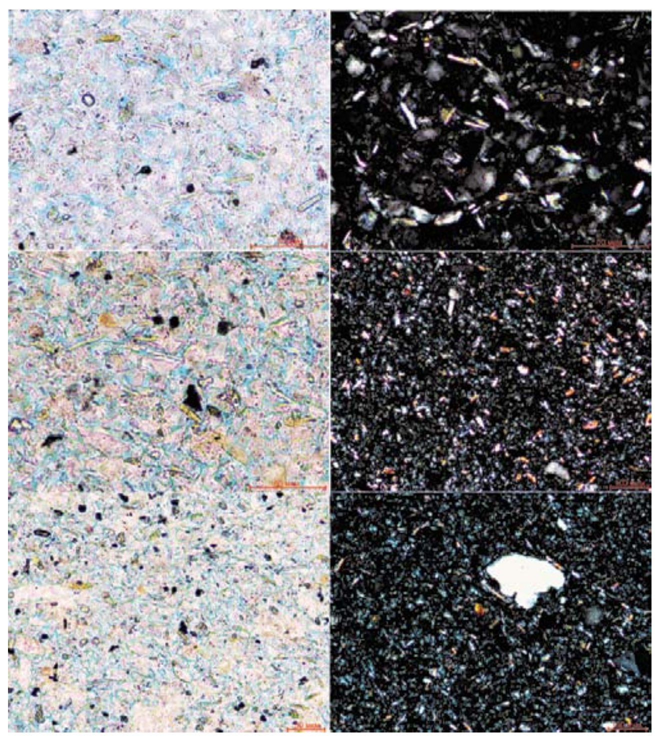

*Fig. 4. General view of the aleuropelitic rock outcrop "Masali" (left – parallel Nicols, right – crossed Nicols).*

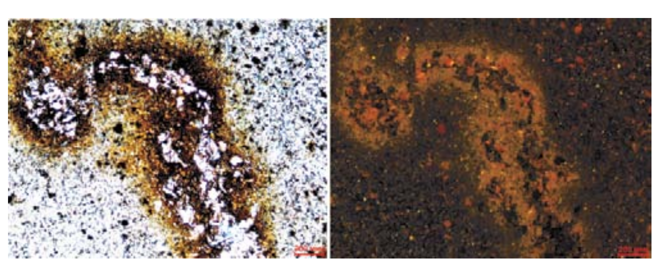

*Fig. 5. Moves of burrowing organisms (left – in direct light, right – in the reflected light).*

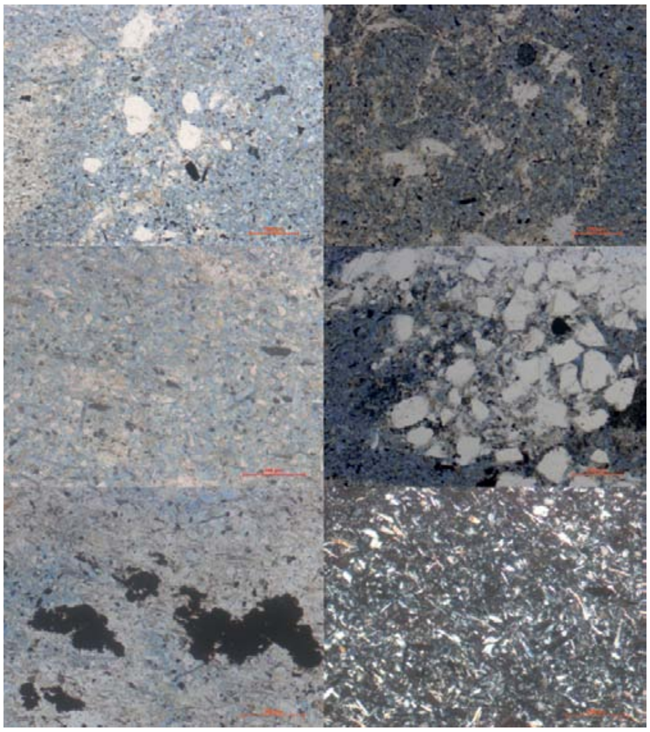

*Fig. 6. General view of the aleuropelitic rock outcrop "Pyatkovo" (left – parallel Nicols, right – crossed Nicols).*

slightly higher content of sand fraction. Aleuropelites are light gray, heterogeneous, weakly lithified, mica, with an admixture of sand fraction (2-4 %). The main rock mass consists of small quartz, with a predominant size of 0.01 to 0.03 mm, with a small admixture of feldspars (orthoclase, less plagioclase) of the same size (Fig. 6).

Sand bodies are arranged in the form of irregularly shaped lenses and consist mainly of poorly rounded quartz grains with individual grains of feldspar (plagioclase, slightly leached). The lenses also compose of siltstone admixture and grains with a good roundness. The grains of quartz are with no apparent trace of postsedimentary changes. Grain size ranges from 0.01 to 0.12 mm (0.25 mm predominant grain size).

The rock has irregular alternation of layers rich in kaolinite, which, as a result, is denser than layers of fine rock. In the volume of rocks we can see an abundance of fine elongated grains of mica minerals, mainly weakly altered biotite. Grains of quartz are often isometric, although elongated grains are frequent. From authigenic minerals: chlorite, kaolinite, hydromica minerals, pyrite concretions unit, up to 0.05 mm. There are rare grains of epidote.

The layered rocks are disturbed. As in the rocks exposed in other outcrops, there are signs of burrowing organisms. On one level with lens of sandy material (along conventional bedding, weakly guess) coalified organic residues are common (small carbonaceous detritus).

## Discussion and conclusions

The studied rocks are loose, almost entirely composed of angular grains of quartz, predominantly pelitic and silt dimension with a small admixture of large fragments and small number of clay cement. This description in lithological science is applied to marshallites that further argues earlier suggested statement that these rocks should be seen as the marshallites (Molchanov, Yusupov, 1981).

This fact, combined with the consistency of rocks in large parts gives grounds to consider the Ishimskian deposits as a source of natural microsilica in the south of the Tyumen region and exploration object for siliceous raw material (Smirnov, Konstantinov, 2016).

The results of these studies do not record significant differences in the lithology of the studied rocks. The rocks are identical in their mineral composition and structural-textural features, confirming the generality of the formation conditions. The totality of the available data indicates that the Ishimskain suite is an integral sedimentary rhythm.

Formation of Ishimskian sediments probably happened in a lake shallow water at constant fluctuation of water level, resulting in a constant flow-through and high oxygen potential of surface water, determined the intensive washing, elutriation and bleaching of clay material that took place under conditions of low-amplitude movements of the basement (Astapov, 1977; Panova, 1971).

Outcrop Masali the only studied area that has two-part structure, where aleuropelites-marshallites are blocked by clayey silt, heterogeneous in composition, origin and genetic relationship of which with the underlying rocks is not yet clear.

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# Weathering Crust of the Basement in Parametric Wells 50 Novournyak and 2000 Tuimazy in the South-Tatar Arch

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**Abstract.** The paper deals with allocation of the vertical profile of the weathering crust based on well logging in the Precambrian basement of the South-Tatar Arch in the Republic of Bashkortostan. Within the most elevated part of the basement in the region, crystalline rocks lie at depths of 1650-3000 m. Despite the fact that the weathered rocks are potential reservoirs, they were not objects of special studies in the Republic of Bashkortostan. One of the reasons is in poor study of core section. The exceptions are parameter wells '2000 Tuimazy' and '50 Novournyak', in which the core was taken out in several intervals of the weathering crust. Based on the comparison of logging data and rock material in these wells the areas were allocated of subsequent change of crystalline rocks under action of supergene factors from the initial disintegration of the initial substrate to the final products of its decomposition. In the well 50 Novournyak rocks alternated in the surface conditions are blocked by the most ancient sediments – Tyuryushevskian suite of the Lower Riphean. The authors believe that the basic pack of the suite presented with quartz-feldspathic sandstones and quartzites and visibly separated from the overlying sandstones according to logging completes a full profile of the weathering crust. In the well 2000 Tuimazy the weathering crust is overlapped by deposits of Koyvenkovskian horizon and is characterized by a greater degree of alternation and fragmentation of the initial substrate. Its formation in the gap between the Archean-Proterozoic and Lower Devonian was a multi-staged: with periods of complete or partial erosion, with the imposition of supergene processes in the previously formed areas. Despite some differences, the vertical profile of the weathering crust in both wells has similar logging characteristics. It is recommended to check signs identified on more wells drilled within the South-Tatar arch, and in the case of confirmation, they can be used to study the structure of the weathering crust in low coring or its absence.

**Keywords**: South-Tatar arch, basement, weathering crust, area, parametric well, crystalline rocks, logging data
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Currently, weathering crust of the basement of the ancient and young platforms is recognized as a promising oil exploration object. This geological formation is productive in many oil and gas regions of the globe, including in the northern edge of the Dnieper-Donets Basin, where the Precambrian basement weathering crust involves deposits of oil, gas and condensate on Yulievsky, Skvortsovsky, Khuhrinsky and other areas. Inflows of hydrocarbons derived from weathered rocks of pre-Jurassic basement of Western Siberia (Shaimsky, Krasnoleninsky arches) and Paleozoic – Kazakhstan (Oymasha field).

In the Republic of Bashkortostan K.R. Timergazin (Timergazin, 1951) first pointed out on the presence of weathering crust in wells of western areas, determining the genetic relationship of "chekanskian suite" rocks penetrated by well 1 Chekansky, alternated in surface conditions with biotite gneiss of the basement. Despite the fact that the weathered and disintegrated crystalline rocks are a potential reservoir, they were not objects of special studies in Bashkortostan. However, due to the reduction of hydrocarbon reserves in the Paleozoic complexes, identification of new promising horizons is relevant, among which may be weathering crust of the Precambrian basement of the South Tatar arch, where it lies at a depth of 1650-3000 m.

It is known that the formation of the weathering crust occurs in a complex set of effects on the crystalline rocks by supergene factors, among which physical and chemical ones are the most effective: the first is responsible for the mechanical destruction of the source rocks, the second provides the chemical transformation of rock-forming minerals.

In the process of weathering the degree of mechanical and chemical changes in rocks from the bottom up is increased, forming profile of the weathering crust. With long-term continental break, in a warm humid climate and relatively leveled terrain, modified weathering crust is developed, vertical zoning of which reflects the staging of processes from the initial disintegration of the source substrate to the end-products of its decomposition.

After B.B. Polynov (Polynov, 1934) and I.I. Ginzburg (Ginzburg, 1963; Ginzburg, Rukavishnikova, 1951), the works of which helped to form the doctrine of the weathering crust in an independent branch of geology in Russia; many researchers proposed scheme of the vertical profile of the weathering crust (Lapinskaya, Zhuravlev, 1967; Petrov, 1967; Sitdikova, Sidorova, 2011).

Despite some differences, its division into zones requires consistent transition from unmodified crystalline rock to its partial and then complete mechanical degradation, which is superimposed by processes of hydration, leaching, oxidation and hydrolysis. At that, presentation about changes of source rocks by supergene agents, structure of the weathering crust and mineral composition of the profile zones were based exclusively on the study of rock material.

Within the most hypsometrically elevated part of the South Tatar arch in Bashkortostan approximately 400 exploratory wells were drilled that penetrated the basement and its weathering crust to a depth of a few meters up to 20-120 m. In many wells (excluding parametric) core was selected only from the bottom zone, sometimes it was presented with 2-3 intervals, rarely – weathered differences. Certain information about the presence in section of rocks modified by supergene processes can be obtained from the slurry (in the case where it is characterized as a crystalline eluvium).

Poor study of rock material does not give even a general idea about the structure of the basement. However, in all drilled wells, the complex of geophysical studies, technical and methodological support was performed, and its representation has been steadily improving. Since the well logs reflect the petrophysical and petrochemical features of the section, it is possible to identify intervals with varying degrees of decompression, mechanical state of the rock and, in part, its chemical conversion.

The paper (Syngaevsky, Khafizov, 1999) according to field geophysics, supported by a core material, isolated logging facies corresponding to unmodified source rocks (zone "A"), and the successive zones of the weathering crust ("B", "C", "D" and "E") of the pre-Jurassic basement of the West Siberian Plain. Using the proposed signs, we attempted to characterize by well logs the vertical profile areas of the weathering crust in parametric wells drilled on the South Tatar arch – 50 Novournyak (NUN), and 2000 Tuymazy (TMZ), the most studied by a core (Fig. 1).

Source rocks of the upper part of the basement, which have been subjected to supergene changes, in both wells are presented by biotite plagio-gneisses, their microclinized differences and granite-gneisses, well-studied by cores and thin sections.

Biotite plagiogneisses are gray, greenish and pinkish-gray holocrystalline, inequigranular massive rocks with unclear gneissic texture (Fig 2a). The main rock-forming minerals are plagioclase (oligoclase-andesine, 55-75 %), quartz (10-30 %), biotite (3-7 %) and microcline (1-3 %, rarely occurred, in areas of cataclase is developed on plagioclase, replacing it in marginal portions of grains), the content of which varies considerably.

Individual core samples are presented microclinized biotite plagiogneisses, which have higher content of microcline (5-10 %); plagioclase is represented by albite-oligoclase and is 45-60 % of the rock. Structure of biotite plagiogneisses and their microclinized differences is porphyro-granoblastic, lepidoblastic and granoblastic. Accessory minerals are apatite, zircon, orthite, monocyte, rutile. Ore minerals are marked by magnetite and ilmenite.

Granite-gneisses, lifted out from well 50 NUN, are red-colored inequal-crystalline, strong, massive, poorly ungneissed rocks. Rock-forming minerals: microcline – 50-60 %, plagioclase (oligoclase) – 5-10 %, quartz – 15-30 %, biotite – 1-3 %. The accessory minerals are zircon, apatite, magnetite.

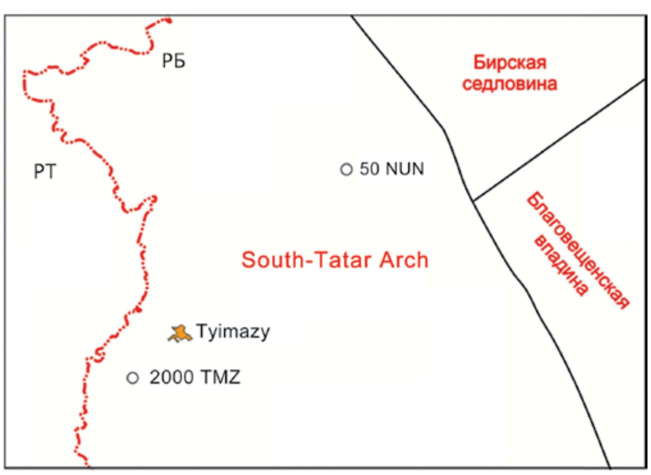


*Fig. 1. Layout of the wells 50 NUN and 2000 TMZ.*

The structure of the granite-gneiss is hetero-granoblastic, profirobalstic-clastic and blasto-clastic.

The characterized differences of plagiogneisses and granite-gneisses contain from 67.47 to 73.70 vol. % of silica, and are acidic rocks (Table 1). In the process of weathering by igneous and metamorphic rocks of the felsic composition hydromica-kaolinitic and kaolinitic types of crust are developed (Kazansky, 1969; Petrov, 1967).

Unchanged by supergene processes source rocks of the crystalline basement (area "A") are characterized by the values of apparent resistivity of the order of 625 Ohm*m (lower the section they may increase significantly). In well 50 NUN zone "A" is clearly recorded from a depth of 2462 meters by lateral logging, which is characterized by uniformly differentiated pattern, varying in the range of 550-7000 Ohm*m; neutron-gamma logging – values reach 7 cu; indications of microprobe reflecting solid rocks. Acoustic log curve is held close to 160 mcs/m, and induction – 90 Ohm*m (Fig. 3).

Core lifted out from intervals 2470.0-2472.0 and 2472.0-2475.0 m is represented by biotite plagiogneiss, red and pink, holocrystalline, inequigranular, massive, with unclear gneiss texture.

In well 2000 TMZ zone "A" begins at a depth of 1837.5 m; below, in the range 1837.5-1840 m, an increase of apparent resistivity from 625 to 1000 Ohm*m is observed, which, judging by the descriptions of the core, is due to the strong

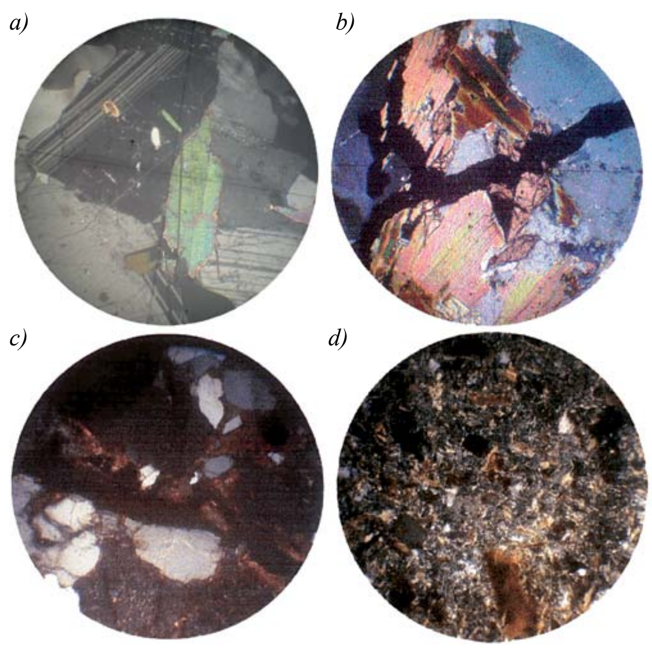

*Fig. 2. Rocks of the weathering crust of the basement, a) Zone "A: – Biotite plagiogneiss. Well TMZ 2000, Int. 2051.6-2055.4 m. Sample 54. Zoom 58. Nicoli +. b) Zone "B" – Biotite plagiogneiss with an open crack. Well 50 NUN, depth 2455.6 m. Sample 336. Zoom 58. Nicoli +. c) Zone "C" – Conglomerate with fragments of biotite plagiogneiss, coarse grains of quartz, microcline and plagioclase cemented by kaolinite-hematite material. Well TMZ 2000, Int. 1811.3-1815.4 m. Sample 21. Zoom 58. Nicoli +. d) Zone "D" – Siltstone very clayish; composed of grains of quartz, microcline, weathered plagioclase and biotite flakes, chloritized. Well TMZ 2000, Int. 1780.0-1781.5 m. Sample 2. Zoom 58. Nicoli +.*

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silicification of plagiogneiss biotite (Fig. 4).

In zone "B" – the zone of initial disintegration, crystalline rocks are at the first stage of discontinuity. Under the influence of physical weathering factors, multidirectional fractures and microcracks are formed, the degree of manifestation of which increases from the bottom up. With the penetration of surface water through fractures containing oxygen, hydration and oxidation processes start. In the chemical composition of rocks the water content increases due to binding it with some minerals; through cracks reddish veins of iron hydroxides appear. But its initial appearance (color, texture, structure) as a whole remained.

In the well 50 NUN zone "B" corresponds to an interval 2462.0-2453.0 m. According to lateral logging it stands out as sharply differentiated curve against the background of values falling between 25000 and 100 Ohm*m and below, increasing the interval time of longitudinal waves travel between 150 and 200 mks/m; Apparent resistivity curve drops from 625 to 125 Ohm*m. In the bottom half of the interval by microprobe more solid rocks are recorded, but at a depth of 2458 m intervals differences between micronormal and microlateral probes are observed; Induction log from a depth of 2456 meters gradually lowers from 90 to 50 Ohm*m.

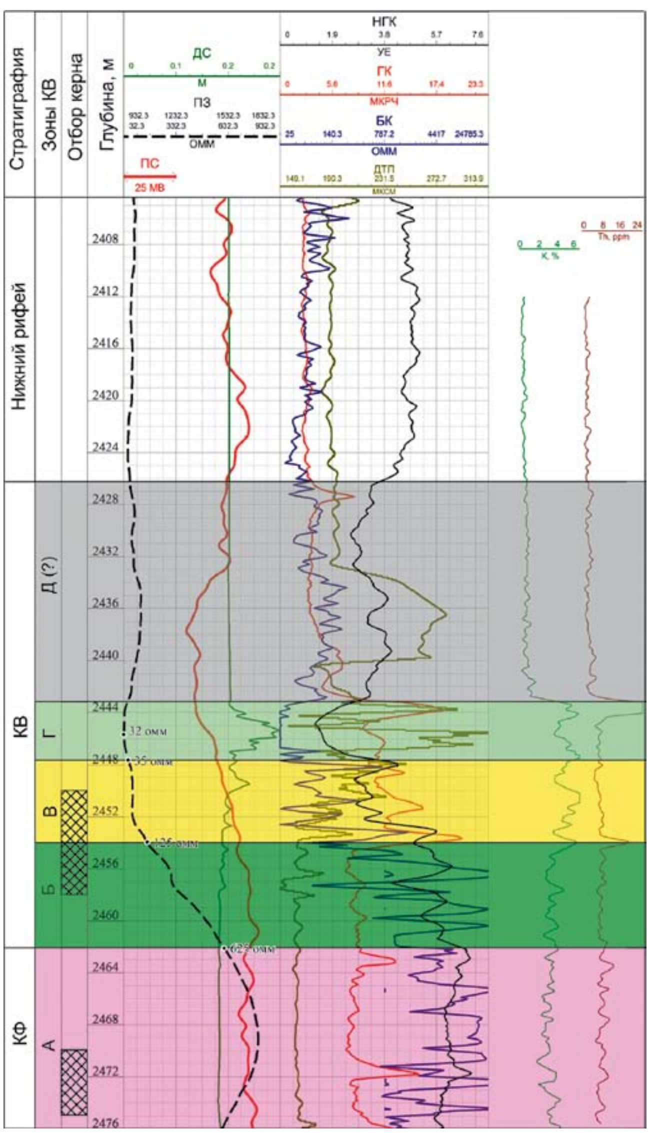


*Fig. 3. The weathering crust of the basement in well 50 NUN (vertical well).*

| Rocks<br><br>Oxides | Biotite plagiogneiss | Microclinized biotite plagiogneiss | Granite-gneisses |
|---|---|---|---|
| $SiO_2$ | 67,47 | 70,50 | 73,70 |
| $TiO_2$ | 0,41 | 0,30 | 0,15 |
| $Al_2O_3$ | 16,34 | 15,59 | 13,30 |
| $Fe_2O_3$ | 1,07 | 0,96 | 0,75 |
| FeO | 2,29 | 1,55 | 1,15 |
| MgO | 2,13 | 1,27 | 0,76 |
| CaO | 4,20 | 2,19 | 1,65 |
| $Na_2O$ | 3,62 | 3,87 | 3,39 |
| $K_2O$ | 1,54 | 2,81 | 4,37 |
| Σ | 99,07 | 99,04 | 99,22 |
| Number of samples | 15 | 44 | 9 |

*Table 1. The chemical composition of the crystalline basement rocks for the well 2000 TMZ (average contents, vol. %).*

From the middle part of the zone (2458.0-2455.0 m interval) biotite plagiogneiss is lifted out with pinkish-gray and reddish pink color, assorted, massive, fractured (Fig. 2b).

In the well 2000 TMZ zone "B" (in the core biotite and biotite microclinized plagiogneiss, weathered through cracks)

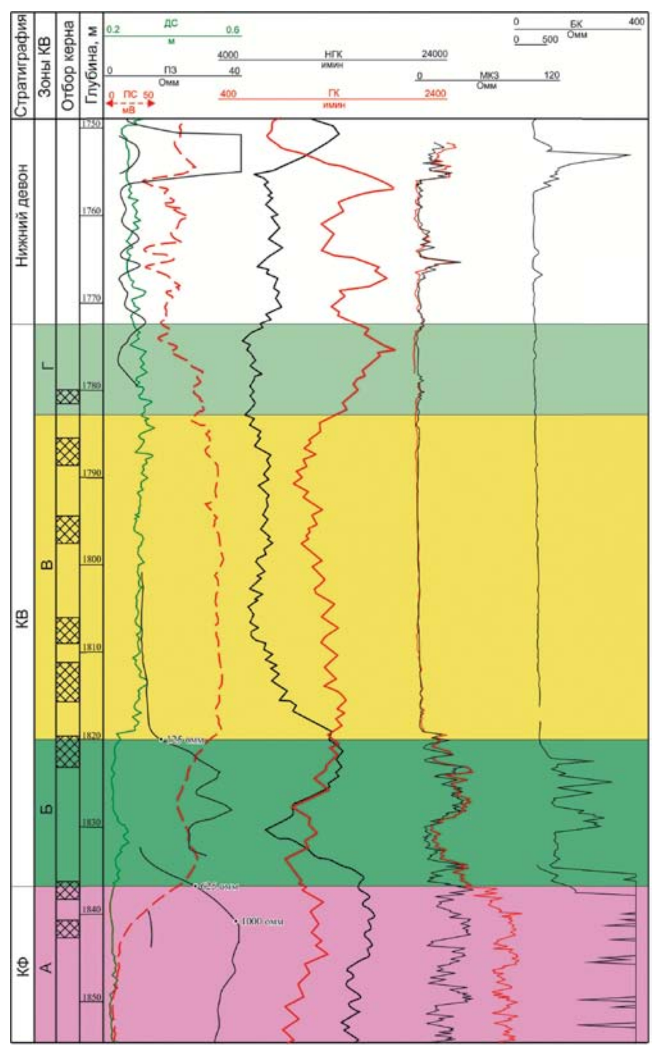


*Fig. 4. The weathering crust of the basement in well 2000 TMZ (vertical well).*

is recorded in the range of 1837.5-1820 m with gradual decrease in apparent resistivity values of 625 to 125 Ohm*m; in neutron gamma log – from 17000 to 14000 cu.

Zone "B" (zone of continuing disintegration and initial decomposition) has the most complex structure. At its base there are numerous multidirectional cracks that penetrate from the "B" zone, but up the section rocks are gradually becoming more mechanically weakened to a complete loss of continuity. The upper part of the zone is composed of breccia and breccia-conglomerate. The fragmentation of the rock increases reaction surface and provides an intensification of hydration and oxidation processes; decomposition (hydrolysis) of silicates and aluminosilicates continues.

Potassium, sodium, calcium are removed from feldspar that go into solution and, subject to leaching regime, are almost entirely (except for potassium, much of which is associated with clay material) removed from the weathering crust. Along plagioclases sericite, muscovite, albite (with decomposition of anorthite component, plagioclase becomes more acidic), hydromica are developed; as the final product of chemical decomposition kaolinite appears. Kaolinite is hydro-micaceous material that weakly cements fragments of crystalline rocks in the upper part of the zone. There is accumulation of iron hydroxides, giving fragments reddish color.

Changes in the physical state of rocks in the zone "B" (interval 2453-2447 m) in the well 50 NUN are reflected by step-down decrease of apparent resistivity from 125 to 35 Ohm*m and increase of the interval time of longitudinal waves travel from 180 to 240 mks/m. In the bottom half of the interval caliper log is held close to nominal value (155.6 mm), above – shows an increase in the well diameter, characteristic for coarse clastic rocks.

Raised core is represented by biotite plagiogneiss, pinkish-gray, holocrystalline, massive, highly fractured; partly rock has a mottled brownish-white color, sometimes it split up to large debris. In thin section, almost all plagioclase grains in varying degrees are pelitized, saussuritized, rarely sericitized; the presence of fine laminal kaolinite and hematite inclusions are identified; biotite is amorphized unevenly, often replaced by chlorite.

In the well 2000 TMZ zone "B" (interval 1820-1783 m) has a large fragmentation of rock compared to the well 50 NUN, which is evidenced by a significant increase in the borehole diameter. Samples of core from the bottom of the interval are represented by conglomerates from fragments of biotite plagiogneiss up to 5 cm; inter-clastic space is filled with a mixture of kaolinite and chlorite, strongly impregnated with iron oxides (Fig. 2c). The upper part of the zone is composed of assorted sandstones and siltstones from the angular and corroded grains of quartz, plagioclase and biotite, cemented by sericite-kaolin material.

Zone "C" is clay, has preferential predominance of the supergene hydrolysis process. It is most typical for the weathering crust and is present in all diagrams of the vertical profile.

Under the conditions of leaching regime a considerable clay starta can be accumulated, mineral composition of which is relatively homogeneous. As mentioned above, the product of weathering of acid metamorphic rocks (which are presented with plagiogneiss granite-gneiss penetrated within the studied area) is kaolinite. Kaolinite mass has undecomposed (more resistant to weathering) primary minerals – quartz grains, fragments of microcline, muscovite flakes, often occurring by lenses or interlayers.

In the section of well 50 NUN clay zone is not characterized by a core, but according to the well logging it is assumed in the range of 2443-2447 m, where the cavity is marked on caliper log (up to 225 mm) and a minimum in apparent resistivity – 32 Ohm*m; decrease in neutron gamma log is observed (up to 1.3 cu) and an increase in gamma log (in the upper part of the zone up to 21 mR/hr). Acoustic log diagram is sharply differentiated in the range of 180 to 310 mks/m.

Involvement of these spectral gamma logging, which allows dividing the section by the presence of natural radioactive elements, showed that high natural gamma radiation of the interval is due to, above all, potassium and thorium content. Potassium, which is released by weathered microcline and biotite, is partly removed from the weathering crust by aqueous solution, but a substantial part of it binds to clay and accumulates in the weathering crust (Alfimova, 2007; ... Mining Encyclopedia, 1986).

Uranium and thorium are present in dispersed form in the crystalline basement rocks, but the content of the first in the continental sediments is very low, because of the high mobility of its compounds under acidic and slightly alkaline environment of the weathering zone. Unlike uranium, "thorium does not go in aqueous solutions and concentrates in the biosphere in insoluble residues of destruction of its more primary discoveries ...", that is, in the weathering crust (Vernadsky, 1927).

In the impurities it contains such accessory minerals as orthite, zircon, xenotime, apatite, monazite; according to microdescriptions they are present in rock samples lifted from the crystalline basement in the wells 50 NUN and 2000 TMZ.

In the well 50 NUN average potassium content in unaltered rocks of the "A" zone is 3.3 %, gradually increasing in the "B" zone to 4.6 %; the maximum values (up to 6.5% or higher) were observed in zones "C" and "D".

As for thorium, its content in the depth interval 2462-2445 m (zones "B", "C" and lower part of the "D") with a few exceptions is held near the mark of 8 ppm, and only in the upper part of the latter there is a sharp increase in readings – to > 26 ppm. Thus, the data on the spectral gamma logging in the well 50 NUN suggest confinement of interval 2443-2447 m to zone "D" of the weathering crust.

In the well 2000 TMZ gamma spectrometry method was not used, but the interval 1783-1772.5 m, presumably corresponding to the area "D", is also characterized by high values of the natural gamma activity and an increase in caliper log. In the bottom part of the interval mudstones are penetrated; according to the microscopic description they are composed of the smallest scales of hydromuscovite and hydrochlorite with an admixture of amorphous clay material, as well as polymictic sandstones with a predominance of poorly decomposed feldspar debris, inequigranular, indistinctly laminated, impregnated with iron hydroxides (Fig. 2d).

Provided intensive drainage, well researched profile of the weathering crust is formed, which ends in the residual zone "E". It is composed of washed by clay material in varying degrees coarse-grained, poorly sorted sandstones with interbedded conglomerates and pebbles. The detrital material is represented by fragments of rocks and minerals, resistant to the effects of supergene factors. The most common residual minerals of the source rock are quartz and microcline, among mica – muscovite; other relics – zircon, rutile, magnetite.

Quartz is also found in new formations of the weathering crust: quartzite and ferruginous quartzite, chalcedony (Ginzburg, Rukavishnikova, 1951). Detritus is cemented mainly by silica or kaolinite. When gets dirty by iron hydroxides rock becomes yellowish-brown.

Zone "E" is very difficult to identify in the section of wells, because even in the presence of core material it is difficult to distinguish from the overlying clastic sediments of the pre-Devonian and Paleozoic; In addition, it is first subjected to erosion.

In the well 50 NUN on clay pack, corresponding to the "D" zone sediments of Tyuryushevskian formation of the Lower Riphean lie. However, the basal part (interval 2443-2427 m) on the characteristics of well logging clearly stands apart from overlying sandstones of the lower strata. This interval is characterized by increased gamma activity (maximum – 7-8 against 3.5 mR/hr), according to spectral gamma logging it is due to thorium and potassium content; significant decrease of the neutron gamma log curve, which is at a depth of 2427 m increased from 3.6 to 5 cu and gains other than the alleged "E" zone nature of the zone. By acoustic log in the middle of the interval 2443-2427 m a pack of about 7 m in thickness is allocated, which is characterized by a sharp increase in interval time to 280 against 180-190 mks/m in the top and bottom, suggesting the possible presence of porous-permeable rocks.

Core from the basal pack was not extracted; according to the slurry it is composed of sandstones with reddish-brown grains of quartzite. By the position in the section, increased natural radioactivity (due to the potassium and thorium), indirectly indicating the relationship with the underlying zone of the weathering crust, we can assume matching of this pack to the "E" zone.

Tyuryushevskian deposits were first allocated in 1966 in the section of well 2 TYuR. As the bottom of the suite was not penetrated (well is stopped in the first dozen meters from the assumed pack "E"), it was not accepted as a basement for the Lower Riphean. The well 50 NUN is the only one in the Republic of Bashkortostan, in which Tyuryushevskian suite is passed completely, including the problematic pack, markedly different from the main column according to well logging.

The weathering crust in the well 50 NUN has a thickness of 35 m (including the "E" zone) and complete vertical profile, zones of which stand out as clear logging characteristics. Its good preservation can be explained by the fact that it was sealed by most ancient sediments in the region of Tyuryushevskian suite of the Lower Riphean, so its age is pre-Riphean.

In the well 2000 TMZ weathered basement rocks overlap Royvenskian sediments, which makes its age pre-Devonian. It is obvious that between the Archean- Early Proterozoic and Early Devonian (2.7-0.4 billion years) the formation of weathering crust occurred in multiple stages; the most ancient crusts were repeatedly subjected to erosion as a whole or in part. Supergene processes are often superimposed on the previously-formed zone, changing the original appearance and eroding the boundaries between them. For example, in the Tuymazinsky well separation of the initial substrate has been recorded in the "B" zone, and the "C" zone is fully represented by coarse clastic rocks.

Well-modified and thick vertical profiles of the weathering crust in the wells 50 NUN and 2000 TMZ have allowed us to suggest that its formation occurred in a humid climate and elevated, stratified relief, providing intensive washing of the weathered crystalline rocks.

## Conclusions

1. Comparison of the rock material and well logging data on the weathering crust in the wells 50 NUN and 2000 TMZ revealed that in spite of the different age and duration of the formation, the area of its vertical profile in both wells have similar logging characteristics.

2. Identified by logging signs are advisable to work out on a larger number of wells drilled within the South-Tatar arch, and if confirmed, they can be used to study the structure of the weathering crust in low core recovery, and even in its absence.

3. The use as benchmark surface of the top of zones uniquely set on well logs, have allowed us to perform correct structural buildings of the basement surface for the South-Tatar arch and for its weathering crust.

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# Arrangement of Concepts About Technological Processes of Limiting Water Inflow into Production Wells in terms of Reagents Used

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We consider water inflow control technology in terms of reagents used. The estimation of technological attractiveness vodoogranicheniya processes based on the use of the most commonly used reagents. According to the analysis reagent compositions are ranked and determined dominant. Recommendations are given to determine the purpose of measures in view of the reagents used, to analyze their effectiveness and, where appropriate, issue guidelines on the most promising technological processes. In view of this it seems appropriate to clarify the current classifier of geological and technical measures.

**Keywords**: chemicals, technological attractiveness ranking of technological processes
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PJSC Tatneft uses a wide range of technologies of water inflow limitation in producing wells. The works are classified in accordance with the accepted classifier. However, upon closer examination it appears that according to the reagent composition, much wider range of chemicals is used in the production than it is provided in the regulatory documentation. This suggests that the real production needs anticipate solutions available in the documentation, and the search for optimal formulations comes intuitively.

We considered 8071 activities, nominally conducted in order to limit the flow of water through the formation, for more accurate composition of the reagents used. Preliminary analysis showed that for 1035 activities reagent composition does not contain a component characteristic for inflow limitation technology from the reservoir; for 1370 activities reagent composition indicates the execution of insulating feeding channel not in the reservoir, but out of production string (it is composed of reagents such as cement, crumb rubber, sand, quartz, etc.).

At least 58 agents were used. The most common were: polyacrylamides – used in 2221 activities; crosslinkers – 1786; SNPKh-9633 – 1492; clay – 1136; liquid glass – 426; RDN – 623. In most cases, injected formulations are complex, usually combining two key reagent determining water limiting essence of exposure (eg, polyacrylamide and crosslinker). Water limiting essence of exposure was to reduce the impact of reservoir permeability by creating low-active highly viscous emulsion (SNPKh-9633, Neftenol, hydrolyzed polyacrylonitrile); scaling in the pore space (water glass, alkali); injection into the pore space of finely dispersed slurry (clay, flour); shutdown of portion of the pore space due to gelation (crosslinking agent with polymer).

Each of the directions is not free from drawbacks. Thus, moving emulsions when putting the well into operation input may partially return into the well, creating complications in production wells transportation. Scaling does not completely cover the pore space. Clay injection substantially alters reservoir characteristics; injected flour does not penetrate deeply into the formation. Gelling covers not only water feeding, but also oil feeding channels and are short-lived due to destruction. Needs to overcome these problems determine a great variety of reagents used.

During the analysis activities similar in reagent composition were grouped, allowing them to continue to be considered as conventional manufacturing processes.

After rejection for these reasons, 4917 activities left. Some formulations are very commonly used (hundreds of activities). However, 542 are few in number (less than 5 activities) and of interest only as a reflection of the attempt to pick up composition, which allows performing the task of limiting the water inflow in specific geological and field conditions of the well. The number of processes is excessively large and, most importantly, in most cases, does not conform to the established governing documents, i.e., illegitimate.

It is relevant to determine the purpose of activities in view of the reagents used, to analyze their effectiveness and, where necessary, to issue a guidance document on the most promising technological processes. In view of this it seems appropriate to clarify the current classifier of geological and technical measures.

Initially, preparation and additional processing of database information was performed. Of the data array on technologies of interest, activities were eliminated with questionable reagent composition, physically incorrect data on the flow rate and water cut. For more adequately characterization of technology, activities were excluded from consideration with too short-term manifestation of the effect (less than three months – the effect was not yet fully emerged) and too long term manifestation of the effect (more than 60 months – the accuracy of determining the end effect is getting worse with time from the date of activity).

For the remaining activities control testing was carried out for recording pump capacity changes after the activity (amount of oil flow rate prior to exposure and average during the exposure of oil flow rate growth should not exceed fluid flow rate prior to exposure).

Conventional technological processes were ranked by the parameter of technological attractiveness, calculated by the formula (1):

$$П_Т = H \cdot K_{ТУ} \cdot \log M \qquad (1)$$

where $П_Т$ is the rate of technological attractiveness, unit; $H$ – relative increase in oil flow rate due to the activity, unit; $K_{ТУ}$ – technological success factor, unit; $\log M_Т$ – logarithm of the number of activities considered for determining technological attractiveness, unit.

Technological success factor is calculated using the formula (2):

$$K_{ТУ} = \frac{M_Д}{M_Т} \qquad (2)$$

where $K_{ТУ}$ – technological success factor, units; $M_Д$ – number of activities with a relative increase in oil flow rate exceeding the threshold, unit; $M_Т$ – total number of measures considered for determining technological attractiveness, unit.

Let us note that this analysis is deliberately removed from the economic characteristics of the results in order to avoid focusing on investment. To answer this question it is necessary to conduct further laborious serious evaluation of technological and economic results of the activities.

Table 1 shows the ranked results of certain processes applied.

The overall picture of water inflow limitation processes application shows that the dominant role in the number of activities is played by clay-based formulations, SNPKh-9633, polyacrylamide (Table 2).

It is interesting to consider a narrower group of processes that use common reagents.

Clay is a part of many technological processes used for water limitation. The technology uses clay property to reduce the reservoir permeability due to siltation. However, injection of clay has a negative side, namely permeability reduction occurs permanently, closing oil feeding channels for oil flow in the future. The use of these technologies at low water content entails the partial production of oil reserves.

A very large number of events are successfully performed using SNPKh-9633. Two main types of composition of SNPKh-9633 – with mineralized water and clay are basically used. Additional analysis shows that clay is used for further fastening of composition SNPKh-9633 injected into the formation in order to prevent its removal into the well at the start of its operation in (especially in fractured reservoirs). The main advantage of the composition based on SNPKh-9633 is its selectivity for water-saturated (formation of highly viscous emulsions in contact with saline water) and oil-saturated reservoirs (oil washing). Experience shows that a major deterrent of emulsion-based technologies application (SNPKh-9633 and others) is their cost. It seems appropriate to intensify efforts to create cheaper technology analogues.

There are advantages for less common processes based on the use of glass. Mainly two kinds of compositions are used: with liquid glass and hydrochloric acid and polyacrylamide to thicken the injected composition, as well as with the addition of flour to prevent removal of the composition into the well (to avoid gelation and salt formation directly in the well). The advantages of the technology with glass are in the relative environmental friendliness and the fact that the reservoir is not sealed tightly, leaving the possibility of further work with the formation.

A wide variety is observed in processes based on the use of crosslinked polymers (polyacrylamide, biopolymer, xanthan and so on). Their advantage is in reliable locking of water feeding channels. However, the effect is not selective, and oil feeding channels can also be locked.

The leading positions on the amount of performed works occupy formulations containing polyacrylamide, crosslinker and RDN (other compounds that do not contain the RDN are markedly inferior). Compositions containing other types of polymers (biopolymers BP-92, xanthan, cellulose) for the amount of work are significantly inferior to polyacrylamide compositions. Let us note that the highest ratings attract the attention on the basis of polyacrylamide formulations with RDN, the use of which traces its history from the time of cooperation with Tatarstan's oil institute "Giprovostokneft".

It seems appropriate to conduct detailed in-depth technological and economic evaluation of the results of these activities in Tatarstan fields. Upon confirmation of the high efficiency it seems appropriate to return to the study of composition and properties of the chemical reagents included in the composition of RDN series, with a view to developing their own technology peers.

| Technology | Number of objects | Rank | Relative increase of oil production rate, un. | Technological attractiveness, un. | Technological success, un. |
|---|---|---|---|---|---|
| Clay, mineral water | 114 | 1 | 9,6 | 19,9 | 100 |
| Clay, mineral water, SNPKh-9633 | 465 | 2 | 6,5 | 17,3 | 100 |
| Clay, ML, mineral water | 17 | 3 | 11,1 | 14,0 | 100 |
| Oil, Clay, polyacrylamide _ thick., water | 31 | 4 | 7,5 | 11,2 | 100 |
| HCl, МЛ, mineral water, SNPKh-9633 | 6 | 5 | 12,9 | 10,9 | 100 |
| Clay, мука, polyacrylamide_crosslinker, crosslinkers | 12 | 6 | 10,1 | 10,3 | 92 |
| Mineral water, SNPKh-9633 | 498 | 7 | 3,9 | 10,2 | 96 |
| Polyacrylamide_crosslinker, ML, crosslinkers, mineral water | 21 | 8 | 8,4 | 9,7 | 86 |
| ML, mineral water, SNPKH-9633 | 95 | 9 | 4,9 | 9,6 | 99 |
| Oil, Clay, polyacrylamide_crosslinker, crosslinkers, water | 73 | 10 | 5,1 | 9,5 | 99 |
| Polyacrylamide_crosslinker, crosslinkers, mineral water | 100 | 11 | 5,3 | 9,5 | 90 |
| SNPKh-9633 | 231 | 12 | 4,4 | 9,0 | 92 |
| Polyacrylamide_crosslinker, crosslinkers, mineral water, guar | 29 | 14 | 4,6 | 6,8 | 100 |
| Oil, Clay, polyacrylamide_crosslinker, crosslinkers, mineral water | 30 | 15 | 4,6 | 6,7 | 100 |
| HCl, product-119, HF, mineral water, water | 8 | 18 | 7,1 | 6,4 | 100 |
| Oil, Neftenol, mineral water | 5 | 19 | 7,9 | 6,1 | 100 |
| Polyacrylamide_crosslinker, RDN, crosslinkers, water | 151 | 21 | 2,9 | 6,0 | 94 |
| Oil, HCl, HF, RMD | 11 | 24 | 5,1 | 5,5 | 100 |
| RBK, crosslinkers, water | 7 | 31 | 5,0 | 4,2 | 100 |
| HCl, zeolite, water | 17 | 35 | 3,7 | 3,8 | 82 |
| Product-119 | 42 | 36 | 3,0 | 3,8 | 79 |
| Biopolymers, crosslinkers, water | 116 | 37 | 1,9 | 3,7 | 96 |
| Glass, hydrolyzed polyacrylonitrile | 13 | 40 | 4,6 | 3,5 | 77 |
| Clay, alyumochloride, polyacrylamide_crosslinker, ML, crosslinkers, water | 6 | 42 | 4,0 | 3,4 | 100 |
| Oil, glass, HCl, polyacrylamide _ thick. | 8 | 45 | 3,8 | 3,2 | 87 |
| HCl, product-119 | 23 | 48 | 2,6 | 3,0 | 91 |
| Glass, HCl, polyacrylamide _ thick., ML, water | 5 | 53 | 3,5 | 2,7 | 100 |
| Biopolymers, crosslinkers | 52 | 54 | 1,8 | 2,7 | 87 |
| VNP | 8 | 61 | 3,0 | 2,5 | 87 |
| Glass, HCl | 37 | 62 | 2,3 | 2,5 | 70 |
| NaOH, polyacrylamide _ thick., ATcF-75, mineral water, water | 28 | 70 | 1,7 | 2,2 | 89 |
| Crosslinkers, KF-Zh, water | 18 | 76 | 1,8 | 2,0 | 89 |
| Zeolite | 13 | 81 | 1,8 | 1,9 | 92 |
| Flour, polyacrylamide_crosslinker, crosslinkers | 10 | 87 | 2,1 | 1,7 | 80 |
| Hydrolyzed polyacrylonitrile, water | 10 | 88 | 2,7 | 1,7 | 60 |
| Glass, HCl, flour, polyacrylamide _ thick., mineral water, water | 13 | 89 | 2,1 | 1,7 | 69 |
| Oil, ahydron, mineral water | 16 | 90 | 1,4 | 1,7 | 94 |
| Polyacrylamide _ thick., ML, neonol-AF, others, water | 5 | 103 | 1,7 | 1,3 | 100 |
| Crosslinkers, xanthan, water | 9 | 105 | 1,4 | 1,2 | 89 |
| polyacrylamide_crosslinker, ML, neonol-AF, others, crosslinkers, water | 5 | 113 | 1,2 | 0,9 | 100 |
| Oil, Neftenol, distillate, CaCl2 | 6 | 120 | 1,3 | 0,7 | 67 |
| Karfas | 5 | 123 | 1,5 | | 60 |

*Table 1. The application results of certain technological processes. Note: polyacrylamide_thickened used to prevent premature sedimentation of composition components, polyacrylamide_crosslinker is used to form the gel.*

| | Reagent composition | Number of objects |
|---|---|---|
| 1 | mineral water, SNPKh -9633 | 498 |
| 2 | clay, mineral water, SNPKh -9633 | 466 |
| 3 | SNPKh-9633 | 232 |
| 4 | oil, RMD | 187 |
| 6 | polyacrylamide_crosslinker, RDN, crosslinkers | 143 |
| 7 | biopolymers, crosslinkers, water | 117 |
| 8 | clay, mineral water | 115 |
| 9 | polyacrylamide_crosslinker, crosslinkers, mineral water | 101 |

*Table 2. The considered technological processes*

## Conclusions

1. According to the reagent composition much wider range of chemicals is used in the production of works than it is provided in the regulatory documentation. This suggests that the real production needs anticipate solutions available in the documentation and the search for optimal formulations comes intuitively.

2. Number of technological processes is too large and in most cases does not conform to the established procedure governing documents. It is relevant to determine the purpose of measures in view of reagents used, to analyze their effectiveness and, where appropriate, to issue guidelines on the most promising technological processes. In view of this it seems appropriate to clarify the current classifier of geological and technical measures.

3. The dominant role in the number of activities is played by clay-based formulations, SNPKh-9633, polyacrylamide. However, injection of clay, despite the low price, has the negative side – permeability reduction occurs permanently, closing the oil feeding channels for oil flow in the future. The main advantage of the composition based on SNPKh-9633 is their selectivity for water saturated and oil saturated reservoirs; the main constraint is cost. The main drawback of compositions based on cross-linked polyacrylamide is nonselective against oil-saturated and water-saturated reservoirs.

4. It is advisable to conduct detailed evaluation activities for a more adequate assessment of the advantages of technologies.

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# Improving the Development System in the Block 4 of Deposit No. 31 of Romashkino Field According to the Logging Reinterpretation and Simulation

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**Abstract.** This article describes the works carried out in the oil and gas production department "Dzhalilneft" to optimize the development of oil reserves from block 4, deposit No. 31 of the Romashkino field. Based on the logging reinterpretation, geological structure of the deposit is adjusted to make rational technological decisions and development of geological and engineering operations. Reinterpretation results of old geophysical data allowed correlating geological section on layers and adjust the previously constructed maps for development of Bobrikovian Lower Carboniferous. The work was performed to identify, study and further map erosion 'incisions'. Based on the results of the reinterpretation of old geological and geophysical data for each well, change the values of reservoir characteristics of productive intervals, effective-oil-saturated strata, we obtained growth of oil reserves. According to the new geological model of block 4, deposits No. 31 the measures are suggested to optimize the placement of project wells for production drilling; wells are recommended for side and horizontal sidetracks, as well as geological and engineering activities for penetration of reservoirs previously unidentified and uninvolved in the development. The proposed measures have helped to reduce the geological and economic risks of drilling of unsuccessful wells, achieve the design level of oil production and oil recovery factor.

**Keywords**: Bobrikovian horizon, geological and hydrodynamic simulation, erosion incisions, hard-to-recover reserves, logging reinterpretation, reservoir properties, reservoir, reserves.

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Development of oil company depends on the replenishment of its resource base at the expense of reserves increment in two areas: further exploration and increase of the oil recovery factor. This problem is under study in the oil and gas production department "Dzalilneft" of PJSC "Tatneft", including by re-interpretation of well logging of drilled wells and on the basis of approved geological and technical actions clarification and development of new ones.

As a result of re-interpretation of old geological and geophysical data for each well there is a significant increase of oil reserves. Modern geophysical methods for studying wells are substantially improved both technically and with software products interpreting the results.

Oil-bearing deposits of Tournasian and Bobrikovian horizons, including deposit number 31, require detailed consideration. The deposit number 31 of Romashkino field is in industrial development since 1977. Experience in operating deposit suggests that there are certain difficulties in achieving estimated oil production rates. The reason is not only in technical and technological aspects of development, but, more importantly, in accuracy of representation of the deposit geological structure. Geological survey of oil and gas production department works to achieve the maximum match of forecast constructions with the actual ones according to drilling data of new wells. In this connection, based on reinterpretation of well logging, well sections are clarified, productive strata and their analogs are allocated, correlation schemes and geological and statistical sections are built (Fig. 1).

According to the results the following is clarified: representation of geological structure of deposit in the structural surfaces, the absolute values of reservoir properties of the host rocks, reservoir distribution by area and section, oil-bearing boundaries and values of effective oil-saturated strata, oil-saturated rock volumes and oil reserves contained therein.

This approach allowed us to adjust the previously constructed maps for development of productive Tournasian, Bobrikian and Radayevskian strata of the Lower Carboniferous for making the most efficient technological solutions and the

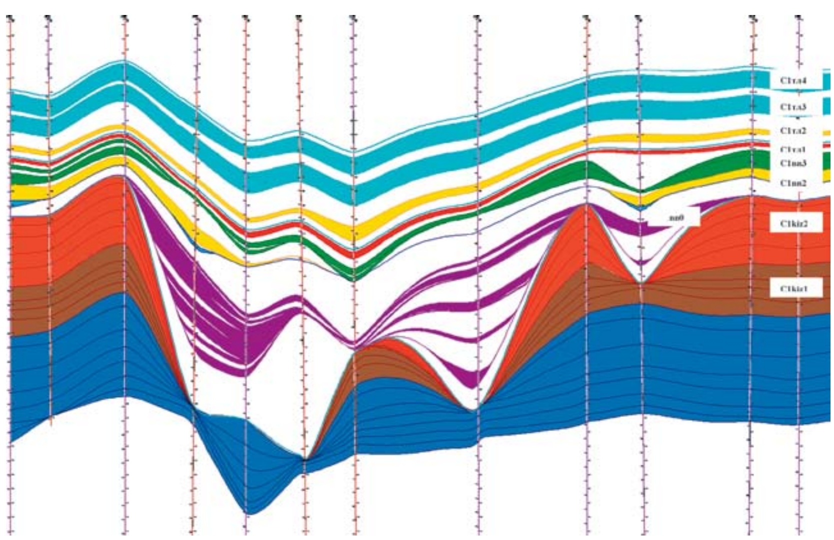



*Fig. 1. Geological and stratigraphic profile of Tulskian-Tournasian sediments.*

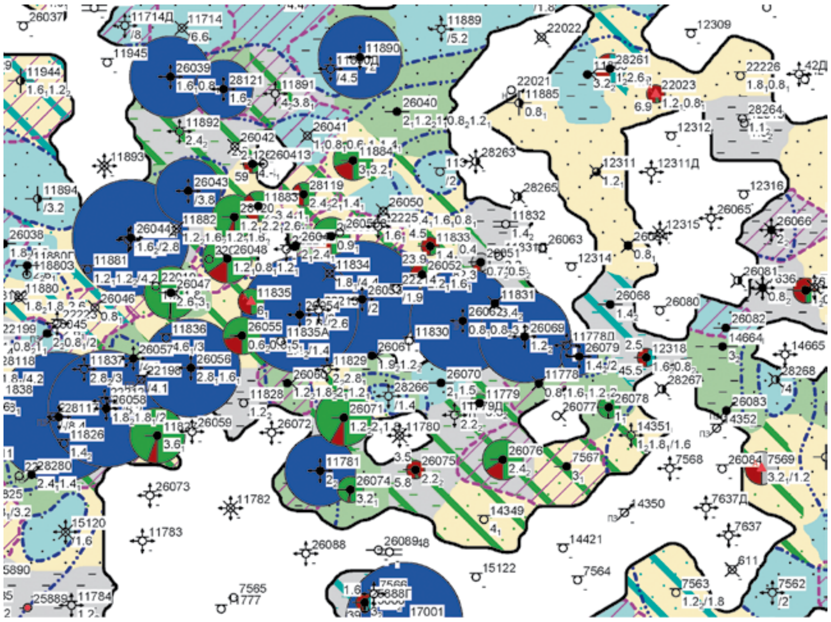


*Fig. 2. Detail of the development map for block 4, deposit 31, formation S1br3.*

development of geological and technical measures to optimize the development of reserves for block 4 of deposit number 31 (Fig. 2).

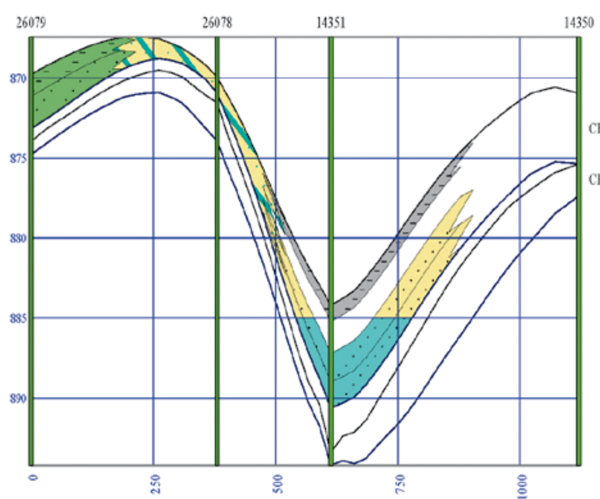
The peculiarity of the structure of block 4, deposit number 31, as well as its structure as a whole, is in the presence of erosion violations in carbonate deposits of Tournasian tier, where a complete washout of Elkhovskian mudstone is recorded, as well as the lack of them in the well section. According to correlation sections and construction of reservoir distribution maps a variety of incisions is indicated on the area in the form of channels, troughs and small areas with different depth of erosion, indicating about the frequent change of depositional environment. Brines of shallow basin, penetrating through cracks and leaching carbonates of Tournaisian tier, destroyed them to the formation of cavities of micro and macro-sizes to karst formations.

Destructed material was washed out to the nearest deflection of Kama-Kinel system. Destroyed zones were filled with terrigenous deposits of Bobrikovian-Radaevskian age, which are associated with elevated values of clastic strata overlying carbonate deposits of Tournaisian stage (Fig. 3). Incision depth to carbonates of Tournasian tier is different: from a few to tens of meters, and complete erosion of Tournasian carbonates and part of the section top of Zavolzhskian Upper Devonian. This is clearly seen in the logging curves, as shown in the example of well No. 14351, where density of isohypses changes sharply on the structural plan, thickness of Tournaisian carbonates are reduced and thickness of clastic formations is increased.

The lack of influence of the injection well number 17001 in Bobrikovian sediments on surrounding production wells may serve as hydrodynamic component to confirm the presence of erosive incision (Fig. 4).

Logging reinterpretation had great value on the allocation of oil-bearing intervals and productive formations, mapping of reservoir distribution (Fig. 5).

As a result of logging interpretation and digitizing, boundary values by oil saturation are clarified that can be attributed to lowering penetration of mud filtrate into the formation. By the results of reinterpretation of old geological and geophysical data for each well, reservoir property values of productive intervals and their conditional values were



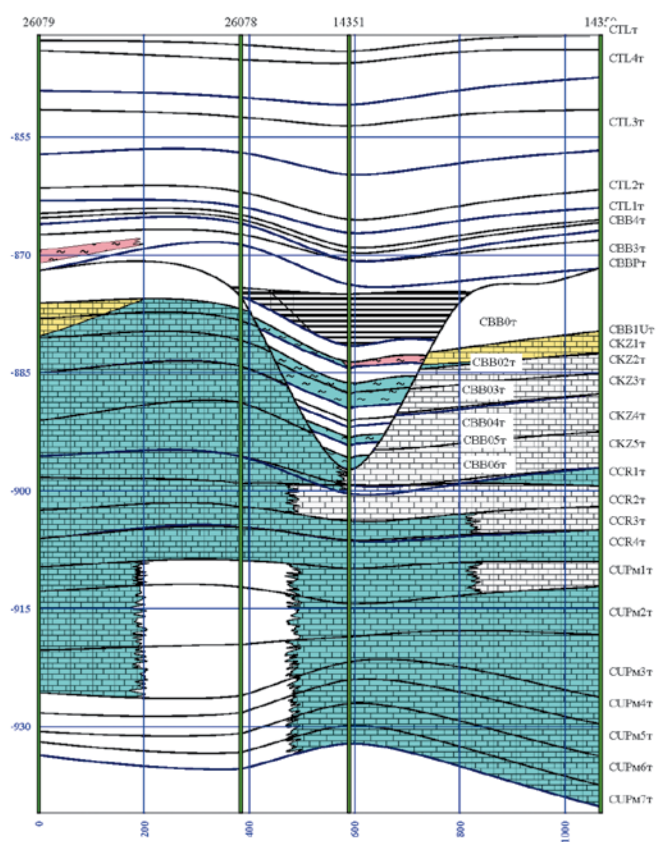




*Fig. 3. Construction of geological sections before and after re-interpretation of well logging.*

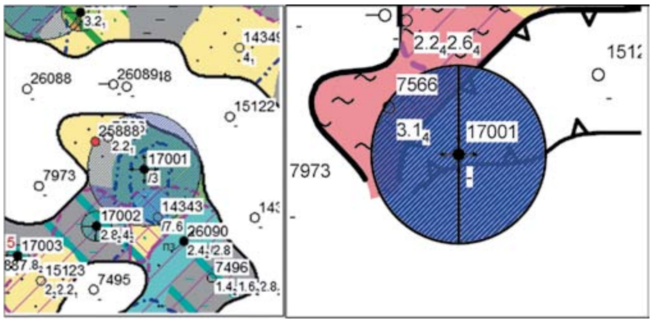



*Fig. 4. Determination of reasons for the lack of influence in injection well No. 17001.*

changed, which naturally led to the refinement of effective, oil-saturated thickness and volume of oil-saturated rocks. As a result, in a number of areas a significant increase in oil reserves is implemented.

Well number 7473 can serve as an example; it was drilled in the productive deposits of Pashiyskian horizon of the terrigenous Devonian. Because of the high water cut of production well was conserved in 1997. According to findings of old geophysical studies for the well number 7473 upper horizons of the section (namely, Upper Devonian Kynovskian and Lower Carboniferous Bobrikovian) stand out as analogs, i.e., characterized by substandard values of reservoir properties.

As a result of this re-interpretation of well logging, sediments S1br2 of Bobrikovian were interpreted as weak oil saturated (Fig. 6). In order to develop reserves on the site in question it was suggested to reopen the well, followed by perforation of the production string in the interval 1143.4-1145 m of Bobrikovian.

Fig. 7 shows a development map of S1br3 formation, based on the results of the detailed correlation of well sections and data of technological performance of their work. In well number 26074 it was offered to produce additional perforation of S1br2 formation, whose occurrence interval on the old loggings was interpreted as an analogue. After digitizing loggings, S1br2 formation is interpreted as clay reservoir with oil-saturated thickness of 2.8 m.

Adjustment of well points of the project fund is no less important result of reinterpretation of well logging and clarification of geological structure of the deposit block. Figure 8 shows the development map fragment with applied

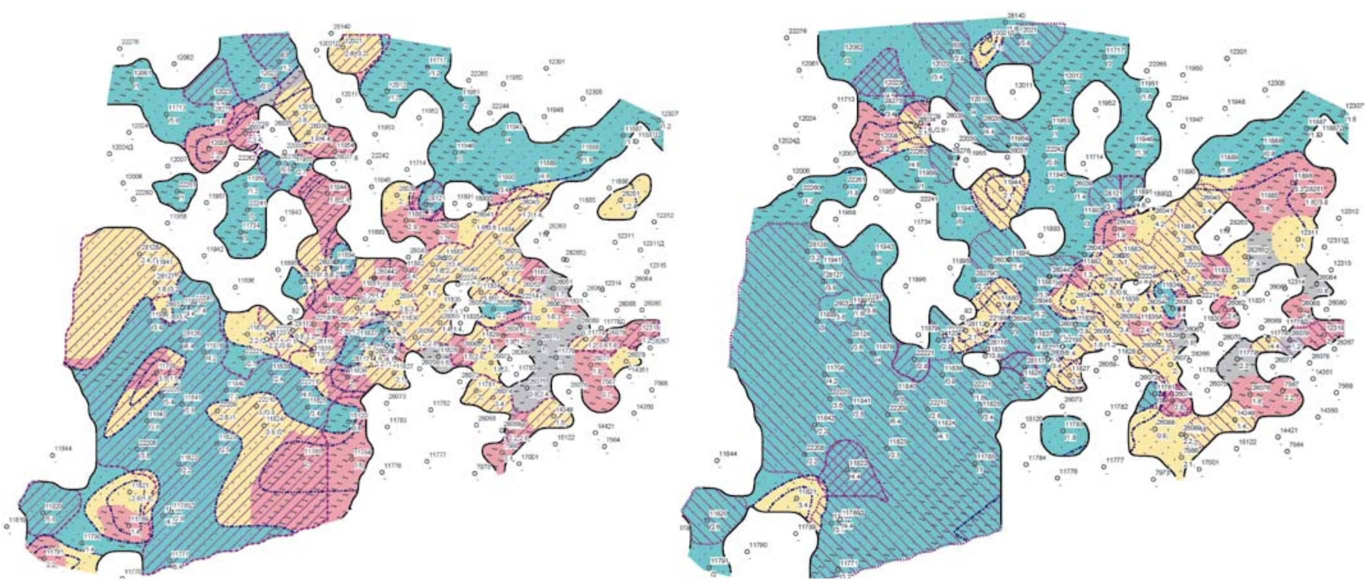


*Fig. 5. Maps of reservoir distribution after reinterpretation of well logging for block 4, deposit 31 of Bobrikovian for the formations S1br2, S1br3.*

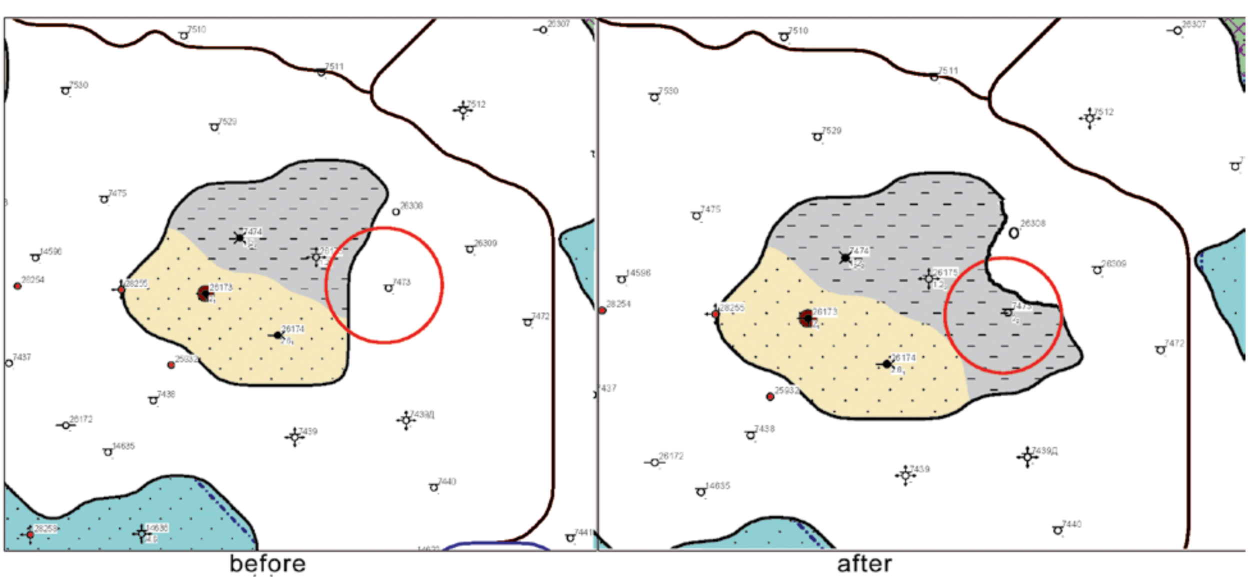



*Fig. 6. Detail of development map for the formation S1br2 before and after re-interpretation of plot for well No. 7473.*

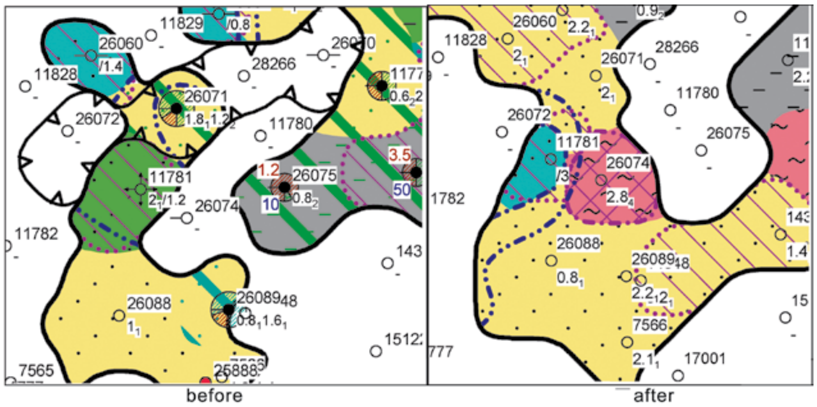



*Fig. 7. Plot of well No. 26074 before and after the re-interpretation of well logging.*

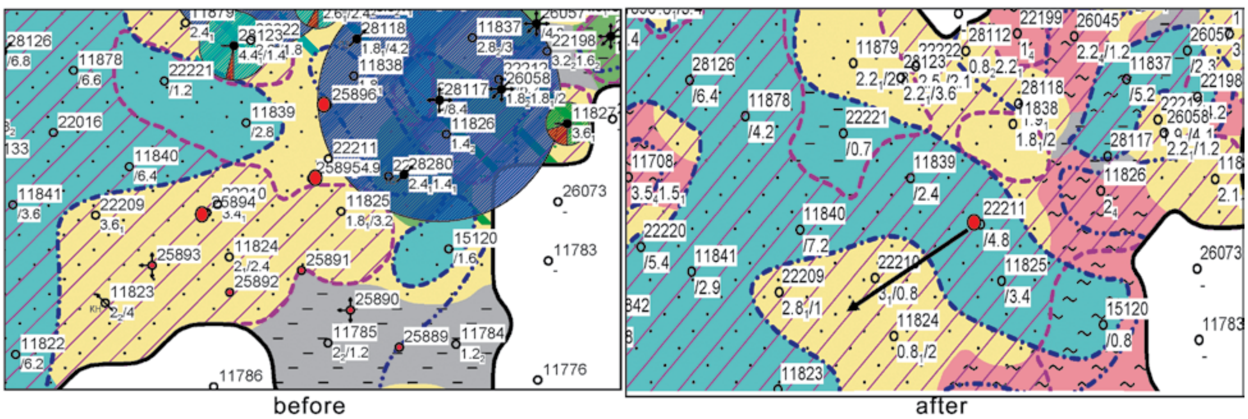



*Fig. 8. Detail of development map for the formation S1br3 before and after re-interpretation of plot for well No. 11825.*

additional project wells for drilling.

According to reinterpretation results constructing of a three-dimensional geological and hydrodynamic model for block 4, deposits No. 31 was performed. Deposit simulation allowed us to obtain new representation on the distribution and occurrence of reservoir rocks and concentration of residual reserves in them.

Construction of various development maps, lithology, reservoir flooding was performed on the statistical data. The difficulties were revealed to determine saturation of certain areas, because most of the wells are working with a high percentage of water cut, though reasons for their flooding are not unambiguous. As a result, the development maps show partially or fully water flooded area, in which the drilling of new wells does not correspond to the current indicators. For such maps, in principle, it becomes very difficult to plan activities, and risky to drill new wells.

In this case, additional geophysical and hydrodynamic studies are provided.

Section of block 4, deposit 31 was chosen for geological and hydrodynamic modeling. After the adaptation of the model, maps were obtained for various parameters in the

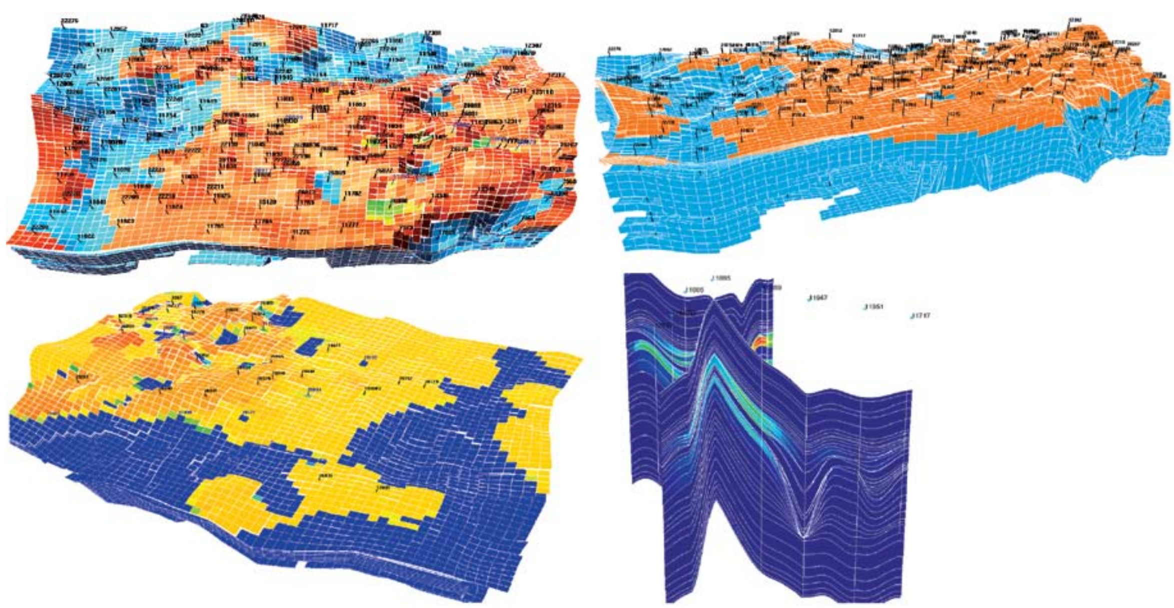


*Fig. 9. Construction of three-dimensional geological and hydrodynamic models.*

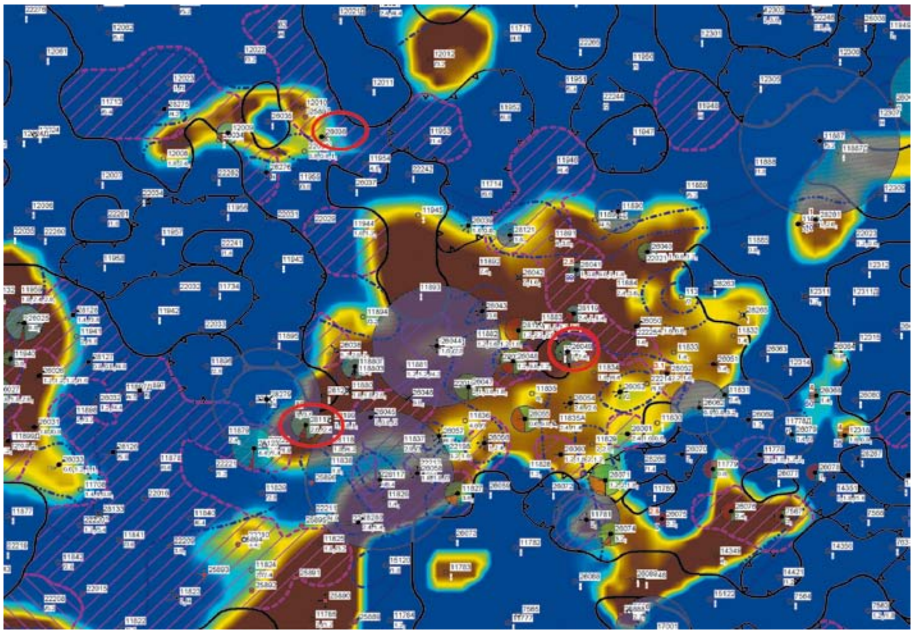


Fig. 10. Averaging of three-dimensional model into two-dimensional model.

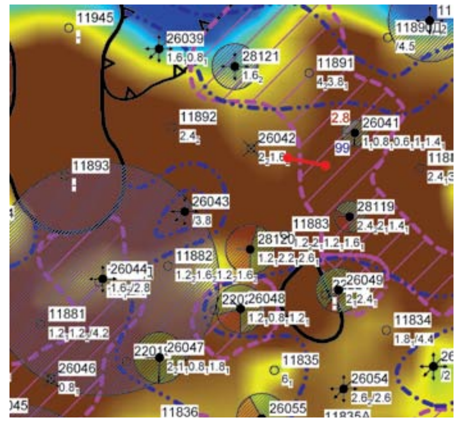


*Fig. 12. Repeated abandonment of well No. 26042 with drilling horizontal sidetrack.*

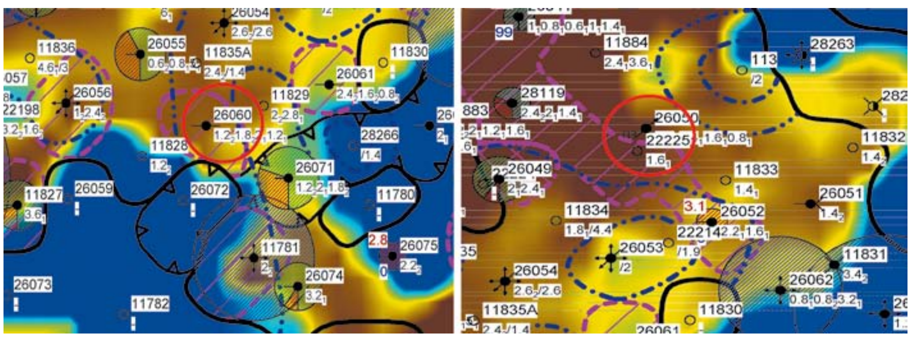


*Fig. 11. Wells No. 26060 and No. 26050, according to the results of research are available for transfer in the production fund.*

three-dimensional visualization. They are maps of initial and current oil saturation, open porosity, permeability and other (Fig. 9-10).

After performed conversions, the analysis of current(residual) oil saturation maps was performed and geological and technical measures were proposed to optimize development system of the block.

Proposed geological and technical measures based on the analysis of new lithologic maps were focused on optimization of project wells location, such as the transfer of drilling point for well 25895 (Fig. 8).

1. When comparing the water cut for neighboring wells and residual oil saturation of the target formation, wells can be distinguished, which require the application of water-isolating techniques.

On the block in question as a result of geological and technical measures wells No. 26036, 26049, 28112 (Fig. 10) are offered for water-isolating operations.

2. Selection of the wells for stimulation or bottomhole area treatments is made as the result of comparing the reservoir properties: porosity, permeability and fluid flow rates, as well as difference between the calculated and actual depression. Wells with identified inconsistencies are usually characterized by a lower flow rate compared to neighboring wells, located in similar geological conditions.

The wells No. 26050, 26060 are recommended for research of IGN to determine the nature of water and oil saturation of reservoirs and according to the results transfer them into a production fund (Fig. 11). The well No. 26042 is recommended to eliminate with drilling horizontal sidetracks in a south-easterly direction from the old bottom (Fig. 12).

Thus, from the above we can draw the following conclusions.

1. Construction of lithological maps according to the detailed correlation provides more informative distribution of lithological bodies in area and section.

2. Digitisation and reinterpretation of well logging of drilled fund allows to:

- Significantly clarify understanding of the geological structure of the target object;
- Adjust the volume and presence of residual oil reserves (in some cases the increment, which is important for the recovery of the resource base);
- Adjust the position of the project wells fund and avoid drilling of empty and highly watered wells.

3. Adoption of new geological and technical measures can:

- Significantly expand the information content of the current state of deposit development;
- The most reasonable plan activities to optimize the existing production system of oil reserves;
- To achieve projected levels of oil production and estimated oil recovery factor.

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# Classification on Morphological and Microanatomical Features of Zircon from Beshpagirsky Field of Rare Metal-Titanium Placers

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**Abstract**: Such parameters as crystal shape, elongation factor and cathodoluminescent image zoning used as petrogenesis indicators helped us to establish the following types of zircon from Beshpagirsky field: metamorphic (5 %), primary magmatic intrusive (S-granites of carbonate-alkaline series 55 %, I-granites of tholeiitic and alkalic series 15 %), primary magmatic effusive (alkaline rhyolite 15 %, alkaline basalts 10 %). At the same time 85 % of the studied zircon grains show signs of secondary changes of varying intensity, which may be due to metamorphism of the rocks from the source area. The first acquaintance with the morphology and microanatomy of zircon from rare metal-titanium placers of Stavropol shows the effectiveness of the chosen method as evidenced by the high incidence of 'typomorphic' zoning for each morphological group. Genetic types of zircon allocated using this method were compared with indigenous species from source areas located in the Greater Caucasus, thus confirming paleogeographic reconstructions made earlier, but also we used their quantitative proportion for specification and contouring of distributive province.

**Keywords**: zircon, morphological classification, cathodoluminescent microanatomy, types of zoning, distributive province
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One of the most common accessory minerals, occurring in almost all types of igneous, metamorphic and sedimentary clastic rocks is zircon. It has a wide range of typomorphic characteristics and is often used as an indicator mineral for petrogenesis. The composition of zircon is very sensitive to changes in the crystallization parameters and even within a single magma chamber may experience significant variations.

Interpretation of geochemical indicative features of zircon grains in the search for sources of supply for rare metal titanium placers is quite precise and time-consuming task. Therefore, available techniques (morphological and microanatomical typing) were used in this study to assess the ratio in placers of plutonic, volcanic and metamorphic zircons from crust, hybrid and mantle rocks.

To optimize the proposed method of morphological and microanatomical zircon typing, as indicator of supplying provenances, the most studied object is selected from a geological point of view – Beshpagirsky field of rare metal titanium placer, which is part of the Stavropol placer district. This placer district is confined to the eponymous arch separating the Terek and Kuban troughs in the Scythian Epihercynian plate.

Paleogeographically, Stavropol placers are located at the southern end of sublatitudinal strait of Medium-Upper Sarmatskian basin that separated the Russian plate from the insular land, which began to actively uplift a Greater Caucasus.

Position of placers in the Stavropol arch (Fig. 1) suggests the existence of a regressive series of shorelines, bending round the centerline of the arch and fixing stabilization phases of sea level in Medium-Upper Sarmatskian paleo-basin (Patyk-Kara, 2008; Kremenetsky, Veremeyeva et al., 2006; Boyko, 2004). It is possible to distinguish at least four such lines, to the south of which Beshpagirsky field is confined, and the two northern (the latest) – Kambulaksky field, Grachevsky and Tashlinsky areas (Rudyanov, 2001).

The ore deposit is confined to Beshpagshirskian suite of Upper Sarmatskian age, folded of layers of fine-grained sands with rare lenses and interlayers of quartz sandstone on carbonate cement and thin interbedded clays and clay sands. The heavy fraction includes ilmenite (40.1 %), leucoxene (10.9 %), rutile (13.0 %), zircon (10.7 %), as well as chromite, magnetite, garnet, epidote, staurolite, kyanite, sillimanite, monazite. The main ore minerals are concentrated in a narrow granulometric class – 0.1 + 0.044 mm.

## Methodology of morphological and microanatomical classification of zircon from Stavropol rare metal titanium placers

The crystals of zircon, preserved elements of cut, were studied by means of widely used typological chart of J.P. Pupin (1980). In this diagram, zircon crystals are classified in accordance with the development in the faceted of individual prism {100} and {110} and pyramidal {211} and {101} forms. J.P. Pupin related the relative development of prismatic faces, mainly with crystallization temperature, while the development of pyramidal faces – with the chemistry of melted material decrystallization.

He drew attention to the fact that typological parameters of zircon populations can be used to describe the evolution of the magmatic system and suggested several genetic interpretations of the chart, adapted for the study of zircon crystals, not only of granitic plutonic origin, but also for zircon of volcanic and metamorphic rocks.

When classifying zircon by morphological features from sedimentary rocks, further features of the crystal structure need to be considered, allowing even conditionally allocate their main genetic varieties. One of these features is the coefficient of crystal elongation (EC). EC value is associated primarily with the growth rate of zircon crystal, as well as the features of chemistry and genesis of the rock, including this mineral. Many researchers noted that EC of intrusive granites often ranges from 2 to 3, EC 3-4 and above is characteristic for volcanic zircon, EC of intrusive crystals for zircon of medium, main substrate – 1,5-2, and metamorphic zircon – 1-1,5 (Liakhovich, 1979).

In the study of rounded grains of zircon at placers that did not keep the elements of cut, EC is the only morphological parameter that should be used for the genetic classification of this mineral. In sedimentary rocks rounded grains of zircon with EC 1 to 2 with equal probability may be of metamorphic, magmatic origin or be rounded fragments of larger crystals.

Therefore, the use of EC in the study of mostly rounded grains of zircon should be advantageously carried out in conjunction with the cathodoluminescence (CL) images of microanatomical structure of these grains. This method, compared to the labor-intensive geochemical methods, is the most affordable and effective enough at genetic classification of zircon from sedimentary rocks, where the identification of contribution share from volcanic, plutonic and metamorphic sources is already an important result.

Figure of zircon zoning reflects the evolution of the crystallization medium of each particular individual and in CL mode depends on the compositional changes of Zr and Si and, more importantly, changes of Hf, P, Y, REE, U, Th – up to the order of the absolute value for some of these elements (Koppel, Sommerauer, 1974; Benisek, Ringer 1993, Hanchar, Rudmck, 1995; Fowler et al., 2002, and many other studies). Along with the CL in the investigation of zircon reverse electron scattering method (BSE) is widely used. Element is mainly responsible for the change in the intensity of BSE, which is Hf with U, having a secondary effect (Hanchar and Miller, 1993).

Both methods identify similar features of the crystal structure; however, bright areas in CL appear as dark in BSE and vice versa (Hanchar and Miller, 1993; Koschek, 1993). With a full range of CL radiation intensity and further changes in color, this method is more informative. It allows identifying the different events of the crystal growth, which often have a characteristic color of CL radiation and allows scheduling areas with different isotopic age (Corfu, 2003).

Each texture segment of zircon retains a specific period in the history of this mineral. Therefore, the interpretation of CL image itself is quite a challenge. At the same time there are a number of ‘typomorphic’ signs of zoning, which can be confidently used in petrogenetic reconstruction – a complex spotty and patchy zoning, wavy zoning, presence of xenomorphic cores, as well as the width and contrast of oscillatory growth zoning, the nature of which is disclosed in sufficient detail in the “Atlas of zircon textures” by F. Corfu (Corfu, 2003).

Efficiency in using tandem parameters such as EC

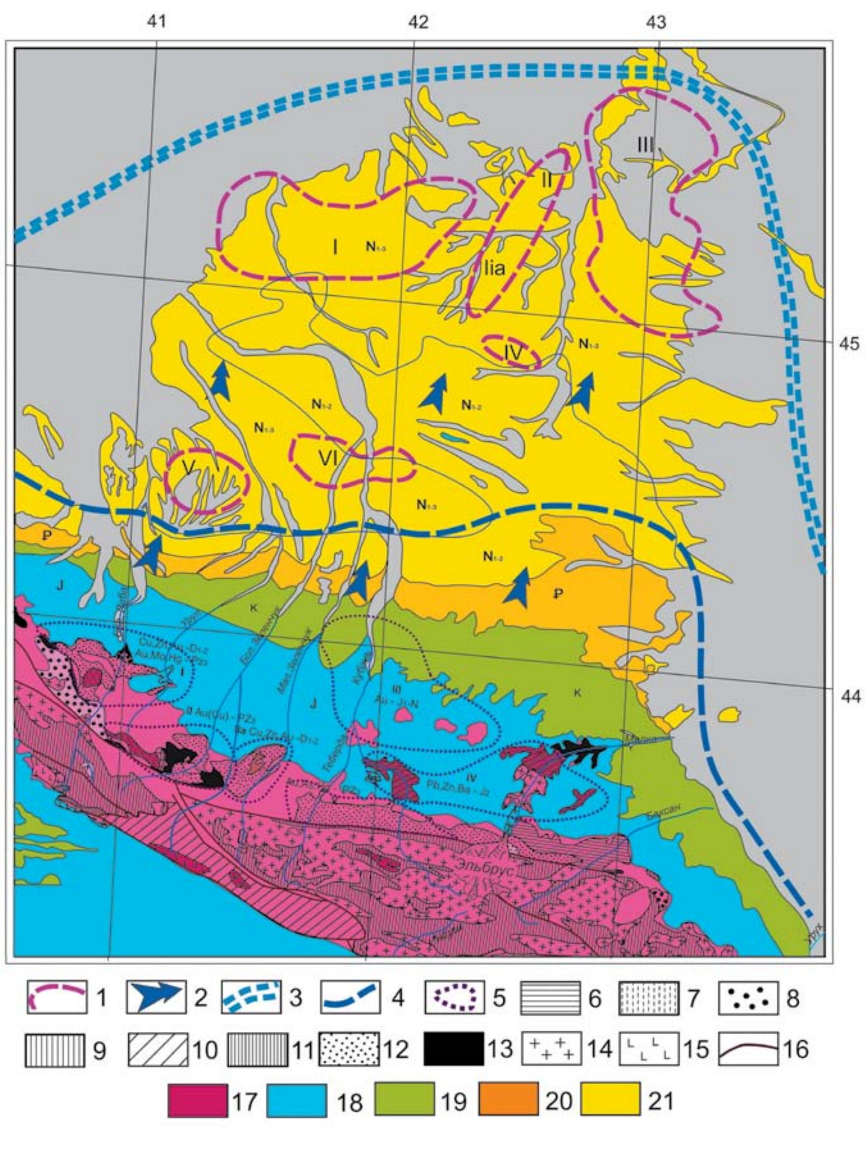



*Fig. 1. Schematic map of geological structure of the Stavropol rare metal titanium placer district with elements of paleogeography of Middle-Upper Sarmatskian time (according to Yashchinin S.B. et al., FGUGP “Sevkavgeologiya” 2004, Somin M.L. (2000) as amended).*
*1 – Placer fields of Stavropol arch (I- Taishinskoe, II – Beitagirsky, IIa – Beitagirsky field, III – Pravoberezhny (Gofitsky, Kambulatsky field), IV – Kalaussky, V – Sinyukhinsky, VI – Nevinnomyssky); 2 – direction of terrigenous material ablation; 3 – average position of the boundary of lithological-facial complexes in shallow zone; 4 – estimated position of coastline of Middle-Upper Sarmatskian basin; 5 – location of ore nodes in the source area (I – Urupo-Labinksky and Andryuksky, II-Marukhisky, III-Mariysky polygenic-polychronic, IV – Kuban-Tyrzylsky, V-Kuchkur-Kishkitsky). Scheme of pre-Alpian base of the Great Caucasus: 6 – Bechasynsky area, Bechasynsky metamorphic complex; 7,8 – Front Ringe metamorphic complexes (1 -Atsgarinsky, 8- Blybsky and its analogues); 9-11 – Main Range metamorphic complexes (9 – Makersky and gneiss-migmatite, undivided, 10 – Buulgensky and its analogs, 11-Labinsky); 12 – Middle and Upper Paleozoic complexes unmetamorphosed complexes of Front Ridge; 13 – ophiolites; 14 – pre-Alpian granitoids; 15 – Batskian and more young granitoids; 16 – main faults. Development area of deposits: 17 – pre-Alpian base of the Greater Caucasus; 18 – Jurassic; – Cretaceous; 20 – Paleogene; 21 – Neogene system.*

and CL-microanatomy as petrogenesis indicators is clearly displayed in this study. In case of petrogenetic classification, in varying rounded zircon crystals from the placers it is possible to allocate grain groups with similar conditions for crystallization by EC value and identify within these groups of grains with "typomorphic" signs and contrasting different patterns of zoning.

## Results

Beshpagirsky placer is dominated in rounded grains of zircon, which did not preserve elements of the cut (56 % of the grains). The surface of most grains is smooth, less rough, with small holes; in a few cases there are grains of irregular shape (Fig. 2). The share of zircon that retained the crystallographic shape, with the ability to diagnose morphotype using chart of J.P. Pupin (1980) amounts to 44 % of the studied grains. The surface of crystals is smooth, often chipped in the form of thin regeneration rims. In accordance with EC value, the following morphological groups of zircon are allocated with EC 1-1,5 (11 %), EC – 1.5-2.2 (49 %), more than 2.2 (25 %), the fragments (15 %).

In the group with EC 1-1.5 rounded grains prevail (Fig. 1. 8-10). The microanatomical patterns of rounded grains of zircon (Fig. 3) are characterized by the following typomorphic features: complex spotted zoning (50 %), transformed primary-magmatic growth zoning (40 %), presence of xenomorphic core and regeneration rims (2 %), rounded fragments of large crystals (5 %).

Among the remaining crystals with EC 1-1.5 (3 %), diagnosed by a typological chart (Figure 4), zircon of morphotypes S8 and S14 is allocated (Fig. 2. 6-7), characteristic for granodiorite and monzogranites of carbonate-alkaline series (S-granites). Microanatomical pattern of such grains (Fig. 3i) retains the features of the primary growth zoning and has traces of superimposed

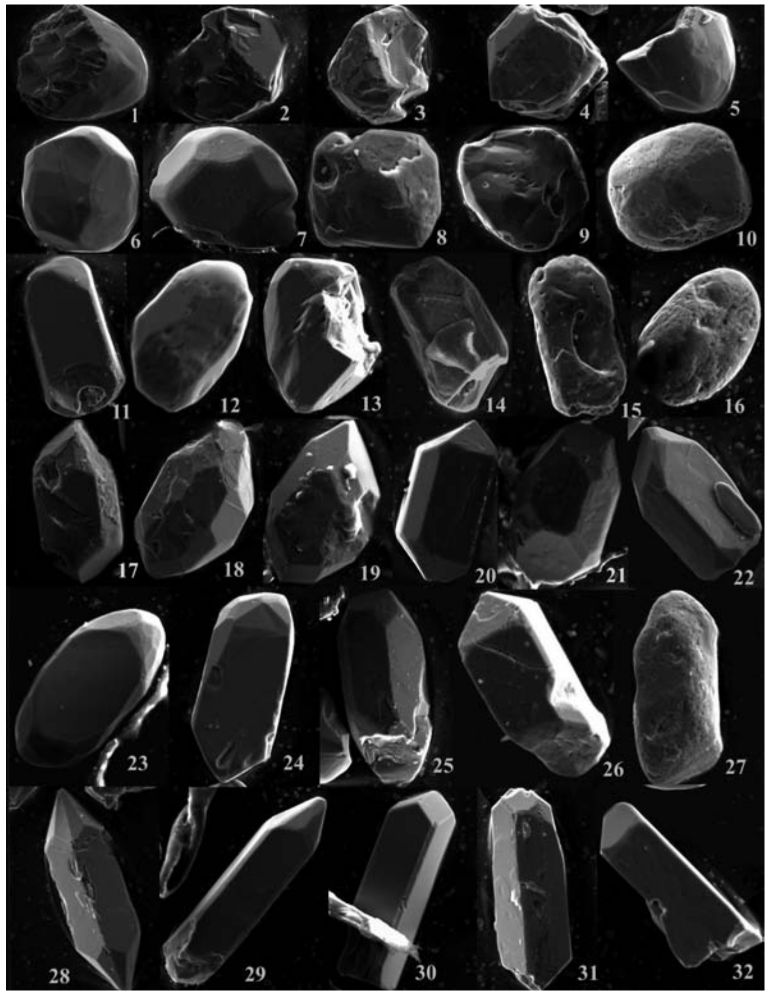


*Fig. 2. Morphological features of zircon grains from Beitagirsky field of rare metal – titanium placers (grain size of 0.1 to 0.063 mm). 1-5 – fragments; 6-10 – EC 1-1.5 (grain 6-$S_{14}$ and 7-$S_8$ with facet elements); 11-22 – EC 1.5-2.2 (11-13 grains with a smooth surface, 14-16 – grains with a rough surface and small holes, 17-21 grains with facet elements); 23-32 – EC over 2.2 (grains 23-26, 28-32 with elements of facet, grain 27 with a rough surface and small holes.*

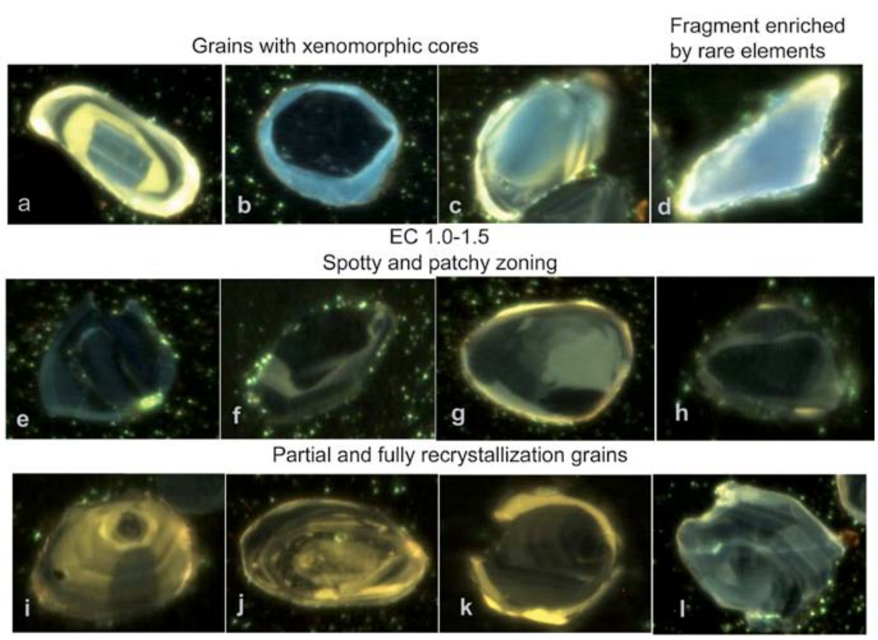
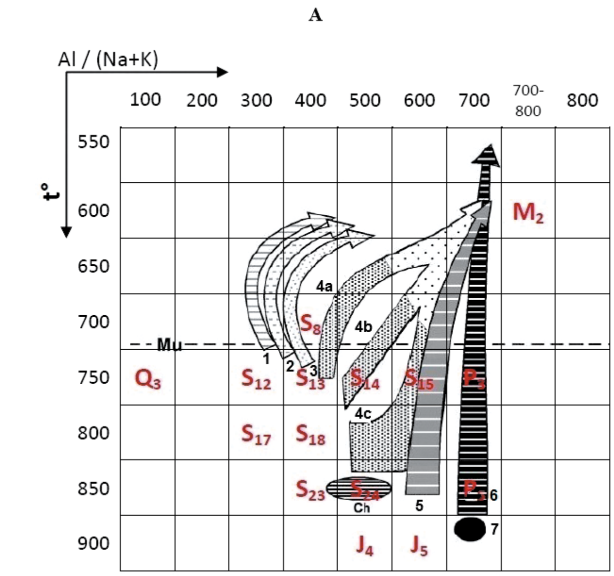



*Fig. 3. Cl-pattern of polished zircon grains from Beshpagirsky field (grain size 0.1-0.071 mm). Grains f I – fragments are referred to this morphological group by zonation pattern. Grain j is referred to the group with EC 1.5-2.2 and exemplified as partial recrystallization grains.*



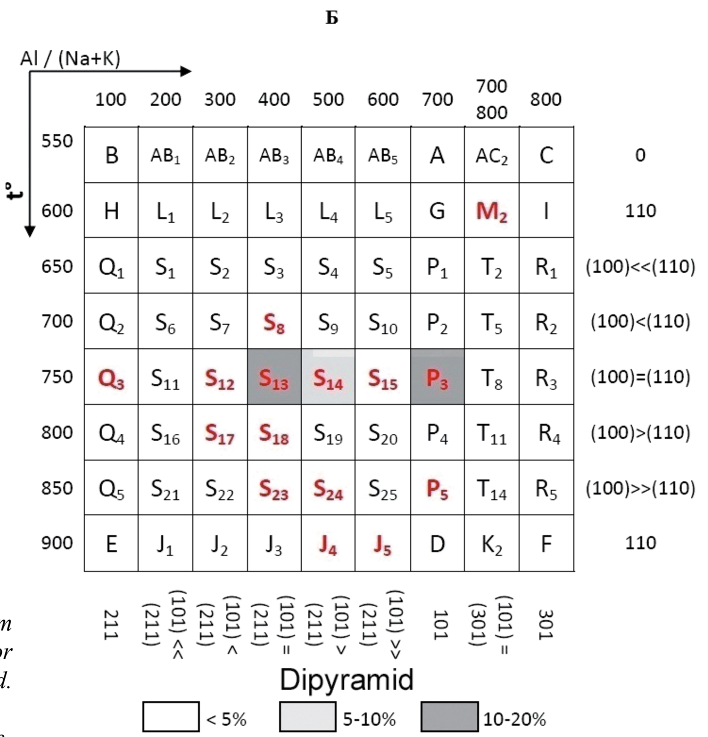




*Fig. 4. Morphogenetic classification of zircon of granite origin from Beitagirsky field according to J.P. Pupin chart (1980). Red color is designated for morpho-types of zircon from Beshpagirsky field. A – morphogenetic typing: Crustal granites (1, 2, 3). Hybrid granites of crustal + mantle origin: 4 (a,b,c.) carbonate-alkaline series (dark field – granodiorite and monzogranites, bright field – monzogranites and alkaline granites), 5 – sub-alkaline series. Mantle granites: 6 – alkaline series; 7 – tholeiitic series. Ch – magmatic charnockites. B – Occurrence statistics of morphological types of zircon from Beshpagirsky field with EC 1.0-2.2.*

conversion processes (dark spots and blurring of the primary sector).

The above typomorphic zoning of zircon with EC 1-1.5 testify in favor of the fact that 52 % of grains of this group have a metamorphic origin, and 43 % of grains are primary magmatic with traces of superimposed metamorphic effects of varying degrees.

In the group with EC 1.5-2.2 grains prevail that preserved appearance of crystals (65 %). Among the established morphological types of crystals (Fig. 4), the most widespread are $S_{13}$ and $S_{14}$, (rarely $S_{12}$ and $S_8$), characteristic to S-granites of carbonate-alkaline series, $P_3$ (with $P_5$, $J_5$, and $J_4$ in subordinate amount) corresponding to I-granites of alkaline and tholeiitic series. In small quantities zircon crystals are marked of subalkalic hybrid granites ($S_{15}$), magmatic charnockitic areas ($S_{24}$), tracheandesite ($S_{23}$ and $J_4$), tonalite (S17, $S_{18}$), alkaline granites ($M_2$) and acidic granites ($Q_3$).

Microanatomical patterns of crystal zoning are growth oscillator, affected to varying degrees by later processes of alternation (Fig. 5). In 75 % of cases there is moderately uniform blur of zoning boundaries. The 25 % has a partial recrystallization with appearance of dark spots and locally modified areas of crystals. In a few cases there are rounded fragments of crystals with anatomical patterns characteristic

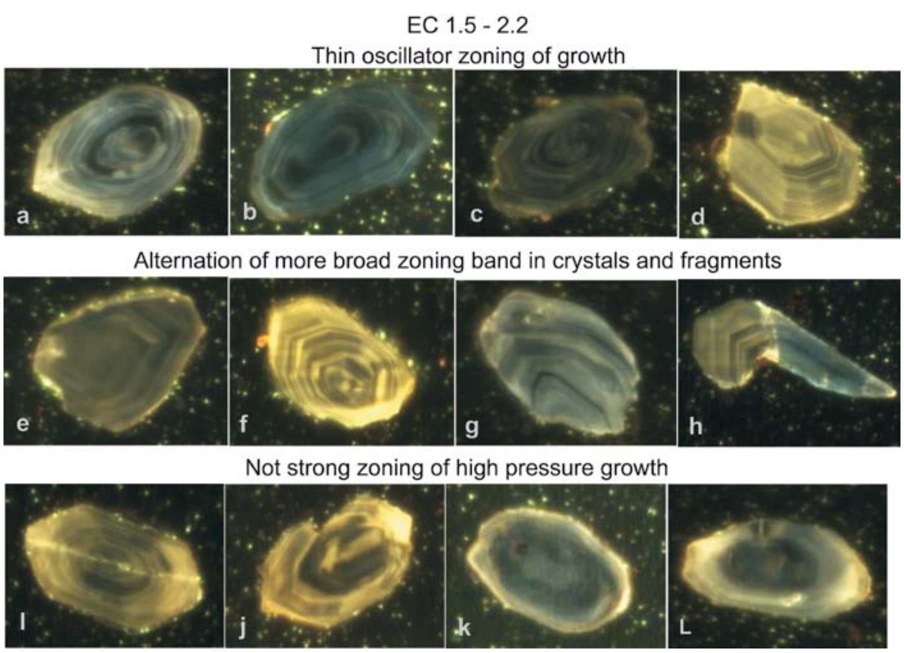
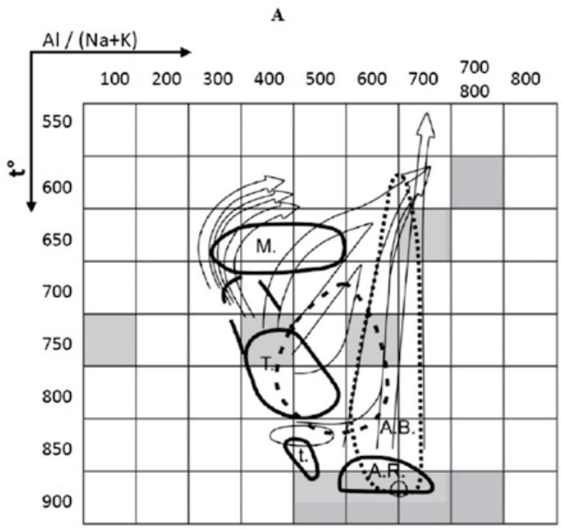



*Fig. 5. Cl-patters of polished zircon grains from Beitagirsky field (grain size 0.1-0.071 mm).*



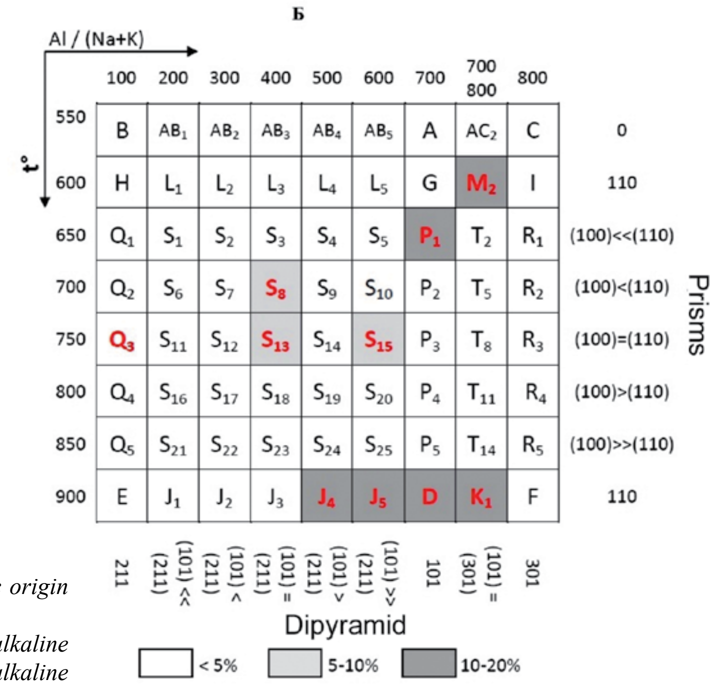




*Fig. 6. Morphogenetic classification of zircon of non-granitic origin from Beitagirsky field according to J.P. Pupin chart (1980). A – morphogenetic typing: (A.B.) – alkaline basalts; (A.R.) – alkaline series of anorogenic rhyolite complexes; (C.A.R.) – carbonate-alkaline series of rhyolite (orogenic): (M) – migmatites, (t.) trachyandesites, (T) – tonalites. Grey color is designated for location of zircon types from Beitagirsky field with EC over 2.2. B – Occurrence statistics of morphological types of zircon from Beshpagirsky field with EC over 2.2. Red color is designated for zircon morphotypes of Beitagirsky field.*

to zircon with EC over 2.2.

Rounded grains with EC 1.5-2.2 (35 %) have rough surface with small holes (Fig. 2. 11-16), and microanatomical patterns are signs of secondary changes in growth zoning.

From the above we can conclude that group of grains with EC 1.5-2.2 has a primary magma genesis and consists of zircon crystals of S-granites from calcareous-alkaline series (70 %), 1 – granites of alkaline and tholeiitic series (27 %) and granites of transitional series (3 %). Zircon grains of all types have traces of secondary modifications of magmatic growth zonation in varying degrees of intensity, as well as thin regenerative rim, covering the surface of crystals.

In the group of grains with EC over 2.2 crystals are marked with preserved elements of the cut (60 %), rounded grains (38 %), elongated-prismatic fragments (2 %).

Among the morphological types crystals are distributed with tetragonal prisms {110} and dipyramid {101} in combination with {211} and {301}, complicated by additional elements of the cut characteristic to morphotypes $J_4$-D-K (Fig. 2, grains 26, 31, 32). This morphological series, in our opinion, is effusive and according to the genetic chart, distribution of zircon of non-granite series by J.P. Pupin (1980) corresponds to the alkaline series of anorogenic rhyolite complexes (Fig. 6).

Morphotype $P_1$ is the second most common (Fig. 2. 30), corresponding to alkaline basalt. The same type includes zircon crystals of morphotype $M_9$. The smallest spread in the group with EC over 2 belongs to morphotypes $S_{13}$ and $S_{15}$ – calcareous-alkaline series of rhyolite from orogenic complexes and morphotype $Q_3$.

In the group of grains with EC over 2.2, crystals with recrystallized nucleus and unclear zoning are clearly distinguished (Fig. 7) from metamorphosed rocks (60 %), with banded zoning possibly from volcanic rocks of intermediate composition (40 %).

Zircon study using samples of morphological and microanatomical typomorphic features enabled to set in Beshpagirsky placer the following types of the described

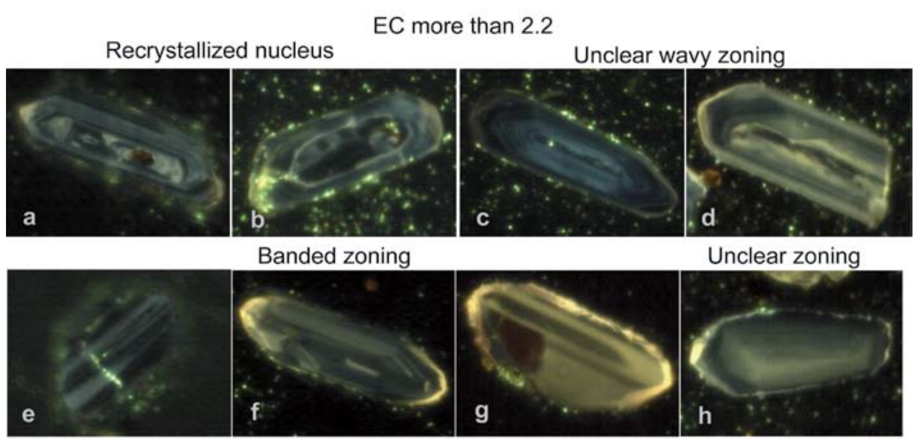



*Fig. 7. Cl-pattern of polished zircon grains from Beshpagirsky field (grain size 0.1-0.071 mm). Grain is e-fragment, referred to the group according to zoning pattern.*

| | Crystallization temperature, C | | | | |
|---|---|---|---|---|---|
| | 600-650 | 700-750 | 800-850 | 900 | Total, % |
| Metamorphogenic | 2,5 | 2,5 | n.d. | n.d. | **5** |
| Magmatic intrusive | | | | | |
| S-type | 2,0 | 45,0 | 5,0 | 3,0 | **55,0** |
| I-type | n.d. | 13,00 | 0,8 | 1,2 | **15,0** |
| Magmatic effusive | | | | | |
| S-type | n.d. | 2,0 | n.d. | n.d. | **2** |
| I-type | 11,5 | n.d. | n.d. | 11,5 | **23** |
| Total, % | **16** | **62,5** | **5,8** | **15,7** | **100** |

*Table. Petrogenetic types of zircon from Beshpagirky field of rare metal-titanium placers according to Pupin chart (1980).*

mineral: metamorphogenic (5 %), primary magmatic intrusive (S-granites 55 %, I-granites 15 %), primary magmatic effusive (alkaline rhyolite 15 %, alkaline basalts 10 %). At the same time 85 % of the studied zircon grains show signs of secondary changes of varying intensity, which may be due to metamorphism of rocks of demolition source.

Another important feature is the absence of distinct metamorphic regeneration rims, with the exception of 4 grains with distinct contrast xenomorphic regeneration cores and rims (Fig. 4-c, k). On the surface of 3 % of grains relics of thin regeneration rims are marked of yellowish color (Figure 5. d, e; Figure 7. d, f, g). It is believed that part of the grains lost regenerative rims during transportation, as evidenced by thin chipped rims on the crystal surface (Fig. 2. 8, 18, 26, 28).

U-Pb dating of metamorphic and regeneration zircon rims (SHRIMP II) of Beshpagirsky field, carried by V.V. Kremenetsky et al (2011), has set the age of regeneration rims as 310 million years, which corresponds to the age of Variscan metamorphism in the Caucasus. Paleogeographic reconstructions (Fig.1) point out on the Caucasus, as the main source of clastic material ablation during the formation of Stavropol Neogene placers. This gives us the possibility of conditional comparison of the data with help of petrogenetic classification of zircon from Beshpagir with the conditions, in which they can be formed in the Caucasus.

## Discussion of the results

The main criteria in determining the zircon provenance were crystallization temperature and geochemical belonging to granitoids of S – and I-type (Table). In the Caucasus, the nature of Variscan granite formation clearly correlates with the crust type: within sialic crust of Bechasynsky zone and especially Elbrus subzone of the Main Ridge S-granites were formed in ensimatic areas of the Front Ridge and crossover subzone of the Main Ridge – granitoids of I – and IM-type. In the first case there was remelting of sialic metasedimentary material, in the second – of mafic. In both cases, the contrast of compositions and P-T conditions of formation of metamorphic belts of these zones is emphasized: low-pressure – high-temperature in the Main Ridge and high-pressure – medium-temperature in the Front Ridge (the Great Caucasus in the Alpine epoch, 2007).

Analysis of the data indicates a predominance of medium-temperature intrusive zircon in Beshpagirsky placer, gravitating to the S-type granites with minor signs of secondary changes. Granites of this type are widely developed in the area of the Main Caucasus Ridge; they are syn – and postmetamorphic granitoids of carbonate-alkaline formation (Fig. 1). Temperature of crystallization of these granitoids is estimated by the authors (Somin, 2000; Petrology..., 1991) at 700-750 °C. Another source of zircon of this type may be unevenly metamorphosed of biotite facies in the north to biotite-garnet facies in the south of sedimentary and volcanic rocks of carbonate-alkaline series of Bechasynsky zone. Rocks of Bechasynsky complex can include effusive zircon of S-type (Table).

The Main Ridge area has widespread gneiss-migmatite metamorphic complex, with temperatures close to granulite. Rocks of this complex can include zircon grains with characteristic microanatomical metamorphic textures and high-temperature intrusive zircon of S-granites.

The second most common zircon in Beshpagirsky placers is zircon of I-granites. Its distinguishing feature is in the development of 'hybrid' elements of facet inherent to multiple high-temperature morphotypes, as well as increasing alkalinity due to cooling of the substrate (Fig. 6). Identified features are characteristic for associations of granitoids of I-type of the Front Ridge and saddle area of the Main Ridge (Fig. 1). Formation of these granitoids is genetically associated with an early stage of subduction zone development as a result of directional changes of the oceanic crust and is in its sequential enrichment of alkalis and magmatism change of tholeiitic series to granitoids of elevated potassium alkalinity (Petrology ..., 1991).

Thus, the source of high-temperature effusive and intrusive zircon of this type could be volcanic, genetically associated with ophiolite associations of the Front Ridge, composing independent zone of Variscan structures of the Great Caucasus. The source of medium-temperature zircon may have been both deep and igneous magma melts of high-alkalinity, which are processing products of ensimatic crust. This assumption may explain the presence of xenomorphic cores and signs of secondary changes in some zircon grains with EC of more than 2.2 (Fig. 7 a, b).

Without exaggeration, it can be noted that the identified genetic types of zircon in general reflect the picture of geological evolution of the whole region.

Statistically, according to the predominance of zircon type in a placer, it can be concluded on the contribution of structural zone in the Caucasus as provenance, provided that the zircon as an accessory mineral found in these rocks in approximately equal concentrations. Referring to the schematic structure of pre-Alpian base of Great Caucasus (Fig. 1) the source area can be conventionally distinguished.

Based on the fact that in studied placers intrusive granites of the S-type prevail, it can be assumed that the main contribution as the source falls on the area of the Main Ridge of the Great Caucasus. Within this zone there are also widespread outcrops of metamorphic rocks of gneiss-migmatite complex, which according to our estimates are a source of metamorphic zircon, the content of which is not large in placer (5 %).

Referring to the schematic structure of pre-Alpian base oucrops of the Greater Caucasus (Fig. 1) it is possible to note that rocks of gneiss-migmatite metamorphic complex in the most part is located in the southern part of this area, and could be water-collecting area from rivers with the southern direction of the flow, while a placer basin in the medium, upper Sarmatskian time was located to the north of the Great Caucasus. Thus, the rocks of this complex, located in the southern part of the Main Ridge were not source areas in Medium, Upper Sarmatskian time for Stavropol placer. While in the northern part, area of the outputs of metamorphic rocks roughly corresponds to the proportion of metamorphic zircon in Beshpagirsky placers.

The main suppliers of detritus from the Caucasus could be paleorivers with a northbound flow, such as paleo-Malka (possibly paleo-Baksan), paleo-Kuban, paleo-Teberda, paleo-Zelenchuki. The beds of these rivers drain the area of the Main Ridge, folded by magmatic and less high temperature metamorphic rocks, the Front Ridge area with ophiolites and associations of alkaline granites and Bechasynsky area with granite of S – type, in varying degrees of metamorphic changes. Outcrop areas of these structural zones roughly correspond to the proportion of zircon of each genetic type, defined in Beshpagirsky placers.

Participation of paleo-Laba, draining the western part of the Main Ridge with the prevailing development of gneiss-migmatite metamorphic complex, and approximately equal to it in size outcrop area of the Front Ridge to the metamorphic complexes and I-granitoids is not likely to have a significant impact on the typical composition of zircon from Beshpagirsky placers, since in its source area zircon of metamorphic genesis and granites of I-type should be present in roughly equal amounts, with the participation of subordinate granites of S-type. Products of paleo-Laba are probably present in placers of western Stavropol placer district, such as Sinyukhinsky and possibly Nevinnomyssky and Tashlinsky (Fig. 1).

Of course, such a comparison at this stage of the study is hypothetical in nature and requires a study of the composition of zircon at a more subtle geochemical level. Further research will not only benefit from more reliable geothermometer, but by means of spectrum of rare earth elements distribution and a set of micro-admixtures will help to detail the results already achieved.

The results of this study complement and coincide with the data obtained in the study of rutile and garnet from Beshpagirsky field (Chefranova et al., 2015). Optimized method of petrogenetic classification of zircon on morphological and microanatomical parameters is recommended for use on less studied placers of Taman Peninsula (Chefranova, Nalomov, 2013; Boyko, Korkoshko, 2003), Ergeny and Dagestan (Matsapulin, Yusupov, 2009; Lalomov, Bochneva, 2006), constituting the Neogene profile of the South Russian placer province.

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# Application of Magnesite Waste in Manufacturing High-strength Ceramics

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**Abstract.** Factories of the Republic of Tatarstan produce about 3 million tons of industrial waste per year. The solution of problem of utilization and processing of industrial waste is to reuse them in the production of ceramics. Currently, however, not all the waste is investigated and can be used repeatedly in industry. The article provides an analysis of magnesite waste, reveals its qualitative and quantitative composition. The effect of the additives from this waste is studied on the following types of clay: fusible clay from Alekseevsky field, refractory clay of Novoorsky field, clay of Salmanovsky field with high carbonate content. In the study we used the following methods: X-ray phase analysis (diffractometer XRD-7000S (Shimadzu, Japan), diffractometer D2 Phaser (Bruker, Germany)), electron microscopy (EVO-50XVP microscope), measurement of basic physical and mechanical properties (press SGP-500 CIM 4 SKB, Stroypribor, Russia, and others). Tests were conducted under identical conditions with the addition of pure magnesium oxide; however, the positive results were not found. Modification of Salmanovsky and Novoorsky clay fields with magensite waste also did not lead to the improvement of the characteristics of the samples. On the contrary, in the ceramic mass compositions based on clay of Alekseevsky field we established the feasibility of using magnesite waste in the range from 2 to 5 % by weight at a burning temperature of 1150 °C for the production of high-strength ceramics.

**Keywords**: magnesite, magnesium oxide, ceramics, clay, modification, low melting eutectics
**DOI:** 10.18599/grs.18.3.15

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## Introduction

According to the concept of long-term development of the Russian Federation for the period until 2020 (Decree of the Government of the Russian Federation of 17.11.2008 N 1662-r) one of the main areas of environmental security is environment of the production. Every year more and more priority is given to reduction of energy and materials through the introduction of best available technologies. On the other hand, it is a fairly complex and lengthy process.

As is known, the Republic of Tatarstan produces about 3 million tons of industrial waste per year. However, the present system of waste management in the republic is based mainly at their burial in landfills and storage in special facilities, which negatively affects the quality of life of the population (Concept of waste treatment in Tatarstan Republic, 2011). The best solution may be to re-use industrial waste in the factories. This will not only resolve the environmental issues that arise in the production process, but also save natural resources.

The problem of disposing industrial waste is enlightened in a considerable amount of works by Russian and foreign scientists (Bender, 2004; Rumi et al., 2015; Khomenko et al., 2014; Salakhov et al., 2014; Sukharnikova et al., 2016; Muller et al., 2009).

The authors considered the task by the use of magnesite waste as an additive for modifying clays, provided by the plant named after A.M. Gorkiy, for the purpose of the waste products implementation in the production cycle of manufacturing ceramics.

## Experimental part

Annually on ship-building plant named after A.M. Gorkiy over 1 thousand tons of waste magnesite is produced, that is a serious problem for its disposal.

This waste is produced from grinding and dry regeneration of molds for the production of castings made of metal alloys; periclase (magnesite powder) is used as a molding composition for making molds from Satkinksy field deposits of PPLF brand with a mass fraction of magnesium oxide of not less than 89 %. The chemical composition of magnesite waste is as follows:

- mass proportion of magnesium oxide is not less than 88 %;
- mass proportion of calcium oxide is not more than 4.5 %;
- mass proportion of silica is not more than 5.0 %;
- other impurities (iron oxides and so on) are not more than 2.5 %.

Industrial waste consists of fine-crystalline grains, 25 % of which pass through the mesh No. 0063 (Specifications number TLT19 on magnesite waste (periclase powder of brands PPLF-89, PPLF-91)).

In the scanning electron microscope "EUO-50" the authors investigated the composition and structure of the waste. The structure of the waste is heterogeneous (Fig. 1-2), fragments are identified of different particle size and morphology. Loose and unstable formations, which are considered to be multicomponent, join together to form conglomerates. The particle size is of about two microns. In some places, formed structures are correlated with fractal (Fig. 2).

According to X-ray spectra elemental composition of magnesite waste varies at different plots. Some fragments differ by a substantial content of sodium metal alkali (Fig. 3). On the other fragments there is a high content of calcium (Fig. 4).

On the white areas of SEM images a complex elemental composition is identified (Fig. 5-6).

For the modification of waste different types of clay were selected: fusible Alekseevsky, refractory Novoorsky, and Salmanovsky clay with a high content of carbonates.

The clay was subjected to pre-dispersing in a dry form before passing through a sieve with a 0.5 mm cell. Then the clay was modified with waste magnesite with mass fractions of 2 %, 5 %, 10 % of the total weight; raw mixes were composed, which were averaged thoroughly in a dry form. After mixing with water operating humidity of initial mass was 10 %. Raw material was prepared by compression (15 MPa) molding.

| Waste composition, % | 0 | 2 | 5 | 10 |
|---|---|---|---|---|
| Density, g/cm$^3$ | 2,2 | 2,3 | 2,3 | 2,2 |
| Water adsorption, % | 1,3 | 1,0 | 1,5 | 1,8 |
| Line heat setting, % | 5,3 | 5,7 | 5,3 | 5,3 |
| Strength, MPa | 139 | 155 | 148 | 103 |

*Table 1. Characteristics of the samples from Alekseevsky clay modified by magnesite waste at firing temperature = 1150 °C.*

Molded samples were kept under natural conditions for 1 day, and then firing was performed at 1050 °C-1150 °C in increment of 50 °C in a muffle furnace LOIP LF-7/13, the firing time – 4 h.

To compare the results for each sample "back-up" was prepared, which instead of the magnesite waste contained the same amount of pure magnesium oxide.

Polymineral fusible clay from Alekseevsky field during firing up to 1000 °C does not form new mineral phases (Fig. 7), with the exception of hematite, which share is less than 1 %.

Determination of the main characteristics of synthesized at 1050 °C materials showed that the addition of magnesite waste contributes to negligible change of physical and mechanical properties in comparison with samples of pure clay.

Samples of clay from Alekseevsky field supplemented with 5.2 % magnesite waste, calcined at 1150 °C in the press test showed high strength properties (Table 1). These results can be explained by the presence in the waste composition of a significant proportion of alkali metal oxides that contribute to the formation of low-melting eutectic, creating an environment for active cooperation.

These results are consistent with the nature of destruction. Figure 8 shows that degradation has occurred as a result of crack growth parallel to the axis of the sample, as evidenced by the shape of fragments and a minor amount of dispersed particles formed (Ariskina et al., 2015).

Tests of samples for compressive strength were conducted on press SGP-500 MGK 4 SKV Stroypribor.

Also X-ray diffraction analysis (XRD) was conducted for patterns with a 5 % magnesite waste from the plant named after A.M. Gorkiy, calcined at temperatures of 1100 °C and 1150 °C (Table 2). As a result of XRD, we can

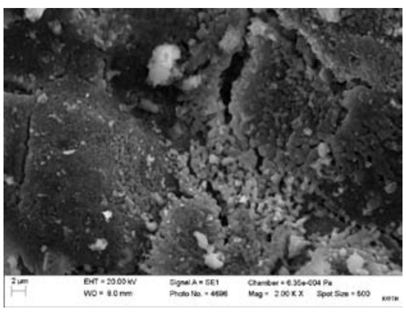

*Fig. 1. SEM image of magnesite waste.*

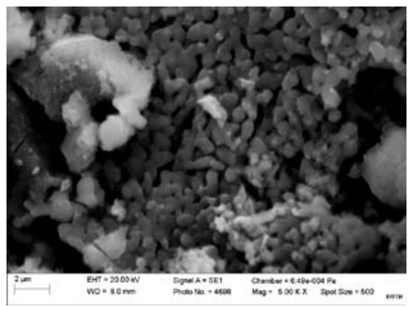

*Fig. 2. SEM image of magnesite waste.*

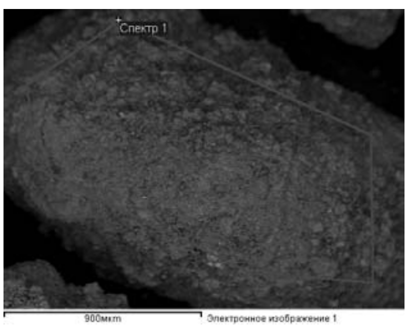


*Fig. 3. SEM image of magnesite waste. The elemental composition of the X-ray part of the spectrum, designated as "Spectrum 1": O – 58, Na – 5, Mg – 29, Si – 6, Ca-1, of Fe – 1 %.*

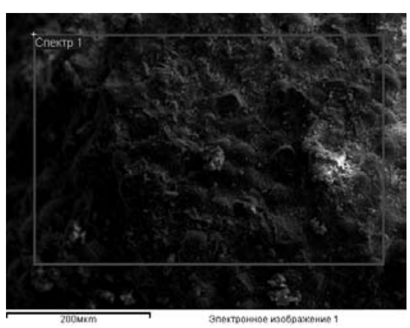


*Fig. 4. SEM image of magnesite waste. The elemental composition of the X-ray part of the spectrum, designated as "Spectrum 1": O – 60, Mg – 27, Si – 8, Ca – 5, Fe – l %.*

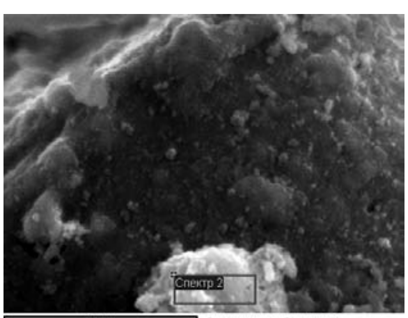


*Fig. 5. SEM image of magnesite waste. The elemental composition of the X – ray part of the spectrum, designated as "Spectrum 2": O – 63, Na – 2, Mg – 23, Si – 11, Ca – 1 %.*

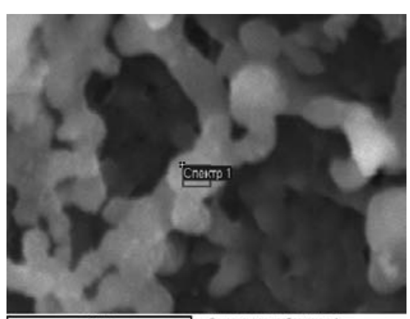


*Fig. 6. SEM image of magnesite waste. The elemental composition of the X – ray part of the spectrum, designated as "Spectrum 1": O – 64, Mg – 21, Si – 11, Ca – 3 %.*

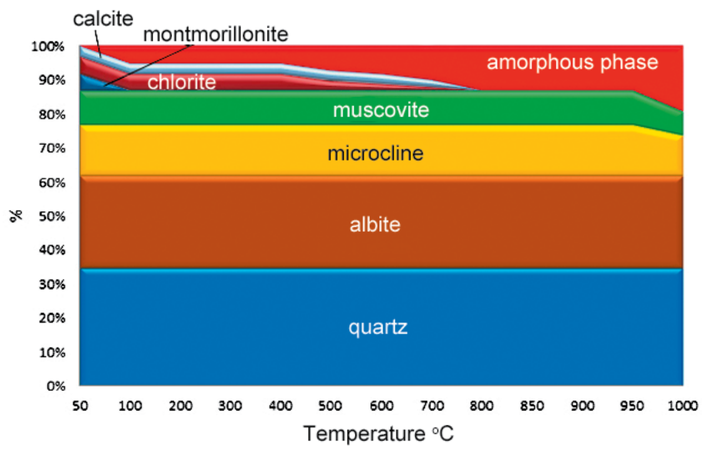


*Fig. 7. Changes in the mineral composition of Alekseevsky clay due to a rise in temperature from 50 to 1000 °C.*

conclude that with increasing temperature in the ceramic samples restructuring occurred. Only stable mineral phases were formed, increase in the share of amorphous phase was identified.

Fig. 9 shows the structure of the calcined sample with 5 % magnesite waste. Noncommunicating pores of about 15 microns are observed. Grains are in close contact with each other, grain boundaries are "glued" as a result of liquid phase sintering to form a monolithic structure.

Analogous studies on the basis of Novoorsky refractory clay and Salmanovsky clay with a high carbonate content resulted in a deterioration of strength

| Burning temperature, °C | Quartz | Albite | Hematite | Periclase | Enstatite | Amorphous phase |
|---|---|---|---|---|---|---|
| 1100 | 44 | 10 | 4 | 3 | 1 | 38 |
| 1150 | 43 | 10 | 4 | 2 | 0 | 41 |

*Table. 2. Mineralogical composition of the samples with 5 % magnesite waste.*

properties. Methods and test conditions were identical.

Variation diagram of the phase composition of Salmanovsky clay in the firing process is shown in Fig. 10.

Salmanovsky clay contains 40 % of calcite, which dissociates with increasing temperature to form calcium oxide. In the firing process, calcium silicate is synthesized. Magnesium oxide, which included in the magnesite waste, does not have a 'partner' in the interaction that contributes to poor strength characteristics.

Variation diagram of the phase composition of Novoorsky clay in the firing process is shown in Fig. 11.

In the firing process mullite is synthesized, which requires a silicon oxide. Thus, magnesium oxide does not have a 'partner' to interact. This leads to a decrease in strength characteristics.

Parallel to studies carried out, properties were identified of the fired samples supplemented with pure magnesium oxide. It was established that the clay composition with magnesium oxide leads to a significant deterioration of performance: when its content is increased to 10 %, a sharp decline in strength by 4 times occurs and the water absorption factor increased by 2.5 times. It can be assumed that most of the magnesium oxide remains unreacted, as evidenced by the white blotches all over the sample volume. Positive results were not found.

*Fig. 8. The destruction nature of the sample with 5 % magnesite waste. Firing temperature = 1150 ° C. Compressive strength – 148 MP.*

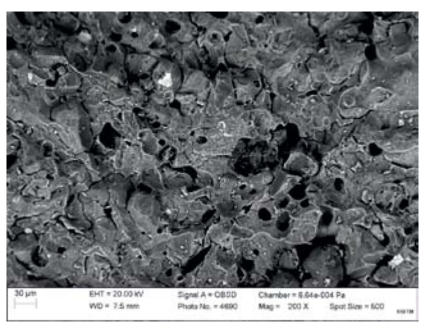


*Fig. 9. SEM image of the sample with 5 % magnesite waste. T = 1150 °C.*

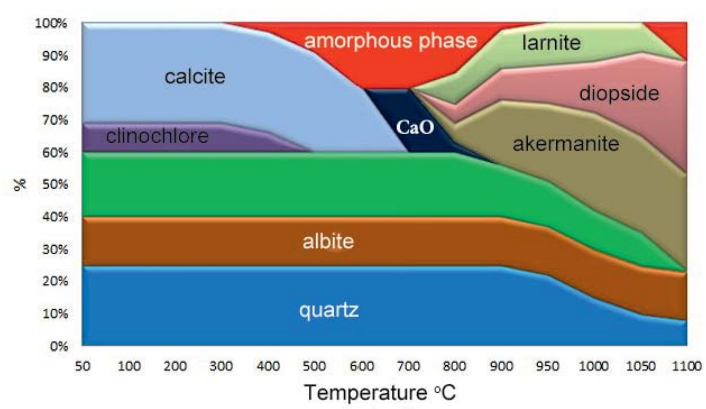


*Fig. 10. Changes in the mineral composition of Salmanovsky clay due to a rise in temperature from 50 to 1100 °C.*

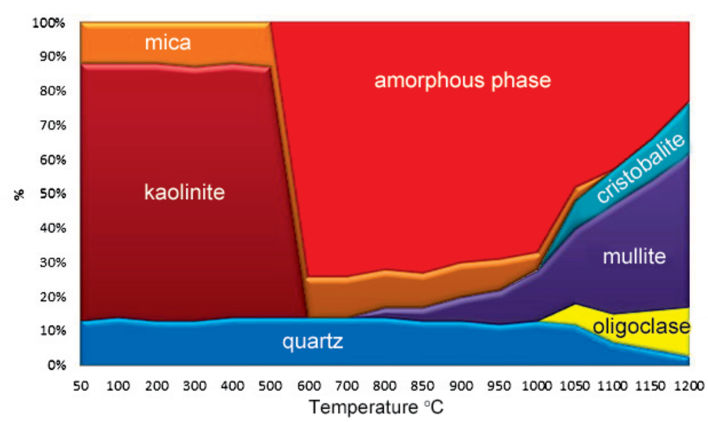


*Fig. 11. Changes in the mineral composition of Novoorsky clay due to a rise in temperature from 50 to 1100 °C.*

## Conclusions

During these studies we established the feasibility of using waste additives of magnesia in the range of 2-5 % by weight of ceramic material compositions from Alekseevsky clay for manufacturing high-strength ceramics, in combination with fusible clay materials ensures completeness and uniformity of sintering at 1150 ° C.

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# Diatomaceous Clay of Shadrinsky deposit (Kurgan Region)

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**Abstract.** Kurgan region occupies a leading position among the regions of the Trans-Urals for reserves of opal-cristobalite rocks. Diatomaceous clay of Shadrinsky deposit is the largest object of the mineral resource base of the region, located in the 1-1.5 km south-west from the city of Shadrinsk, on the right bank of the river Iset at the deep erosional incision. The results of the research revealed that the rocks forming the productive strata of Shadrinsky deposits are represented with just diatomaceous clay, not tripoli, as previously thought. Diatomaceous clay of Shadrinsky deposit is characterized by diatom complex Pyxilla gracilis top of the upper part of Lower Eocene. The general chemical composition of the rocks is close to diatomite of the major deposits of Trans-Urals. The only significant difference is the lower content of the mineral phases SiO2 and greater clay components. The presence of zeolites, calcium-sodium composition (up to a few %) is detected as part of the impurities; the clay fraction is represented by smectite, kaolinite, mica. The bulk rock contains fragments of diatoms in size from 0.005 to 0.063 mm, fragments of siliceous sponge spicules in the size of 0.027 x 0.061 mm in various states of preservation. Features of material composition and microstructure of diatomaceous clay of Shadrinsky field allow us to consider them as a promising raw material for the production of building and insulating materials.

**Key words**: Kurgan region, Trans-Urals, Diatomaceous clay, opal-cristobalite rocks, lithology
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## Introduction

Integrated use of local mineral resources base of solid non-metallic minerals is an important condition for the sustainable development of regions of Russia (Sadykov et al., 2004; 2015). The successful implementation of regional projects in the field of construction, transport infrastructure and agriculture depends largely on the efficiency of extraction, transportation, processing and use of solid non-metallic minerals.

The problem of low-degree involvement in the industrial use of local raw material base solid non-metallic minerals are relevant for the Urals Federal District (Pakhomov, Dushyn, 2008), and especially for the Kurgan region. Despite the favorable economic and geographical position, the presence of impressive and diverse mineral base, traditionally developed agriculture, Kurgan region is among depressed areas of agro-industrial type (Surkov, Shusharina, 2009).

Within the region large deposits are concentrated of bentonite clays, glass and molding sands, semi-precious stone materials, building stone, expanded clay and brick clay. Opal-cristobalite rocks occupy a special place among the objects of the mineral resource base of solid non-metallic minerals in Kurgan region, reserves of which in the region holds a leading position in the territory of the Trans-Urals. Shadrinsky tripoli field was previously explored and developed, balance reserves of 2.2 million $m^3$. Korablevsky tripoli field is known in the vicinity of Kataysk (4.5 million $m^3$), as well as Savinskiy promising area (presumably tripoli reserves – 6.2 million $m^3$) (Natural resources and environment ..., 2015).

Opal-cristobalite rocks are a perspective type of minerals, production and consumption volumes of which increased annually worldwide (U.S. Geological Survey, 2015). Due to a combination of physical properties, diatomite and diatomaceous clay may be in demand in the production of building materials (Nikitin et al., 2014; Radayev et al., 2013), fertilizers and ameliorants in agriculture (Loboda et al., 2014; Aksakal et al., 2012), natural sorbents for the purification of industrial and domestic waste water (Anisimov et al., 2010), etc.

Shadrinsky field is the largest object of the mineral resource base for opal-cristobalite rocks in Kurgan region. In the scientific literature and geological reports rocks that form the productive stratum of the field are described as 'tripoli' (The balance of mineral reserves of the USSR, 1984). The research results presented in this study demonstrate the need for further consideration of rocks from Shadrinsky field as diatomaceous clay, but not tripoli.

## Objects and methods

Shadrinsky field is located in the 1-1.5 km south-west from the city of Shadrinsk, on the right bank of the river Iset, on a site immediately adjacent to the village Oseevo (Fig. 1). The field was discovered as a result of the work of the Ural exploration management in the 1930s of the XX century. Exploration was carried out in pits and wells in the area of 3 $km^2$.

In 1935, according to the passport, reserves were taken in the amount of 1.4 mln. $m^3$. In the 1950-60s additional exploration was carried out to identify new potential sites and recalculate reserves.

As of 2012 reserves of Shadrinsky field according to categories $A + B + C_1$ make 2246 thousand $m^3$. The field is located in the undistributed subsoil fund. Rocks are

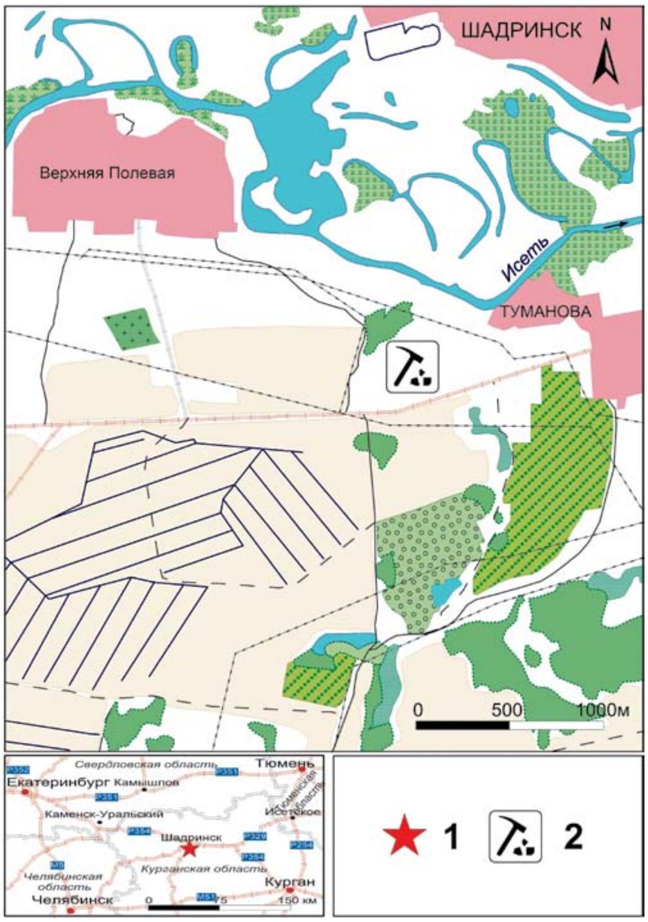


*Fig. 1. Map of the actual material: 1 – location of the research site, 2 – location of an abandoned open-bit mine of Shadrinsky field.*

suitable for the production of expanded clay gravel –filler of light concrete of brands 500, 600, 700. (Natural Resources and Environment ..., 2015). Form of the deposit is tabular, stretched from south-west to north-east. The field area is 1,812 km$^2$. Productive stratum lies directly on the surface of blue clay or thin layer of bluish quartz sand and related to the Irbitskian suite of Eocene; total thickness is up to 40-50 m in non-eroded state under interfluve areas, and from 10 to 30 m within the major erosional incision of river valleys (Vishnyak et al., 2011.); thickness on the Shadrinsky field reaches 12 m.

Stone material for the study was selected from the stripped walls of nonfunctioning open-pit mine. Analytical work included the study of elemental and mineral composition, lithological-petrographic and microprobe analysis, electron microscopy. Work was performed at the Center for collective use of multi-element and isotopic studies at the Institute of Geology and Mineralogy SB RAS (Novosibirsk), the Tyumen Industrial University and LLC "ZapSibGTs" (Tyumen). X-ray diffraction analysis of samples was carried out on the powder X-ray diffractometer ARL X'TRA of company Thermo Scientific ARL Products.

Elemental analysis of geological samples was carried out by mass spectrometry with inductively coupled plasma (ISP-MS) (Nikolaev, 2008; 2012). IR spectra were recorded in the range of wave numbers from 370 to 4000 cm$^{-1}$ in the Fourier spectrometer VERTEX 70 FT IR of company Bruker. X-ray fluorescence analysis of the silicate samples was performed on the X-ray spectrometer ARL-9900-XP of company Applied Research Laboratories. The lithological and petrographic description was carried out in thin sections prepared by the standard method.

## Results and discussion

According to the microscopic and lithological-petrographic research, the rock structure is biomorphic, fine-grained, pelitomorphic; texture – micro-layered, micro-lenticular, bioturbated. The rocks are characterized by diatomacaoues complex Pyxilla gracilis (upper part of the Lower Eocene) (Alexandrova et al., 2012). There are index-species Coscinodiscus payeri Grunow, as well as Paralia crenulata (Grunow) Gleser, Grunowiella gemmata (Grunow) Van Heurck, Pyxidicula moelleri (AS) Strelnikova et Nikolaev, Odontotropis carinarta Grunow, Stellarima microtrias (Ehrenberg) Hasle et Sims, Costopyxis broschii (Grunow) Strelnikova et Nikolaev, Stephanopyxis megapora Grunow, Vallodiscus lanceolata Suto. Presence of clearly defined biomorphic structure requires renounce of accepted in the literature and geological reports lithological description of the rock as 'tripoli' and characterize the rock as 'diatomaceous clay'.

The chemical composition of diatomaceous clay differs in content markedly from the basic components of Trans-Urals diatomite ( %) (Table 1). By the general

| Field | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | BaO | $SO_3$ | $V_2O_5$ | $Cr_2O_3$ | NiO | Ignition loss, % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Shadrinsky (diatomaceous clay) | 66,24 | 0,68 | 13,18 | 5,39 | 0,04 | 2,14 | 0,37 | 0,45 | 1,64 | 0,06 | 0,03 | 0,08 | 0,04 | 0,02 | <0,01 | 9,55 |
| Irbitsky (diatomite) | 77,78 | 0,53 | 8,16 | 2,82 | 0,02 | 0,73 | 0,75 | 0,48 | 1,14 | 0,04 | - | - | - | - | - | 6,81 |
| Kamyshlovsky (diatomite) | 75,2 | 0,57 | 8,09 | 4,38 | 0,03 | 0,73 | 0,81 | 0,44 | 1,18 | 0,06 | - | - | - | - | - | 7,67 |

*Table 1. Common chemical composition of diatomaceous clay from Shadrinsky field and diatomite of Trans-Urals * (Sidorenkov et al., 1989). * Blanks – there are no data or below the detection limit.*

| Be | Sc | Ti | V | Cr | Co | Ni | Cu | Zn | Rb | Sr | Zr | Nb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2,3** | 15,0 | 4600 | 300 | 118,0 | 12,0 | 17,1 | 37,0 | 100,0 | 80,0 | 105,0 | 120,0 | 11,3 |
| **Ga** | **Sb** | **Ba** | **Pb** | **Y** | **Cs** | **La** | **Ce** | **Pr** | **Nd** | **Sm** | **Eu** | **Gd** |
| **15,6** | 0,3 | 274,0 | 14,5 | 15,9 | 5,6 | 18,3 | 35,0 | 4,6 | 17,7 | 3,3 | 0,7 | 2,7 |
| **Dy** | **Ho** | **Er** | **Tm** | **Yb** | **Lu** | **Hf** | **Ta** | **Th** | **U** | **Mo** | **Tb** | |
| **3,0** | 0,6 | 1,7 | 0,3 | 1,6 | 0,3 | 3,5 | 0,9 | 8,3 | 1,6 | 1,8 | 0,5 | |

*Table 2. The results of the elemental composition identification by ISP-MS method, g/t.*

chemical composition, the rocks are close to diatomite from other deposits in the region, the only significant difference is the lower content of $Si0_2$ mineral phases, and more clay components.

The results of the microelement composition of diatomaceous clay from Shadrinsky field are shown in Table 2. The diatomaceous clays of Shadrinsky field are characterized with the values exceeding the clarke contents of the following elements: Mo, Yb, Hf, Cs, Sc and Zn.

As a result of X-ray diffraction (Fig. 2), the main component of diatomaceous clay is opal (amorphous silica) and smectite; there are quartz, mica, kaolinite, a small admixture of plagioclase, jarosite, traces of gypsum and anatase. However, the characteristic opaline halo is less pronounced than that of pure diatomite (Selyaev et al., 2014). Noteworthy is the presence of zeolites of calcium-sodium composition (up to a few %) as a part of impurities.

According to IR spectrometry (Fig. 3) the spectra of all samples exhibit a number of bands due to stretching and deformation vibrations of Si-O-Si bonds and OH groups. The most intense band of asymmetric stretching vibrations of Si-O-Si bonds is 1046 $cm^{-1}$. Shifting of the band (in comparison with typical diatomite) is due to the presence of clay fractions apart from diatome – smectite, kaolinite and mica.

According to the lithological and petrographic analysis, the bulk of the rock (Fig. 4) consists of partially optically oriented particles ranging in size from less than 0.001 to 0.005 mm, with gray and yellow interference color, having microgranular (microglobular), flaky and fibrous structure.

The bulk of rock has a significant number of fragments of diatoms in size from 0.005 to 0.063 mm, flint fragments of the spicules of sponges in size of 0.027 x 0.061 mm.

The clastic material is concentrated mainly in the form of thin micro lenses and intermittent layers, formed as a result of the activity of burrowing organisms, its content is not large in the range of 5-7 % of the area of the thin section; it is represented by grains of quartz, feldspar, biotite and muscovite flakes with grain size of 0.01-0.12 mm. Also the rock contains small, round, yellow-green glauconite grains, the size of 0.03-0.06 mm. Calcium-sodium zeolites, nontronite, pyrite, gypsum, pyrolusite, muscovite and biotite are among the main impurities. The rock is characterized by a high microporosity; pores prevail in size of less than 0.005 mm.

The research results under the electron microscope show that diatoms with a high degree of preservation are not numerous, some of them showing signs of losing its original structure: the bulk is composed of fine detritus (Fig. 4,5). Everywhere on the surface of biogenic residues small flakes of clay minerals are present. Due to the high degree of crushing, other minerals, except quartz are hardly diagnosed in a overall mass.

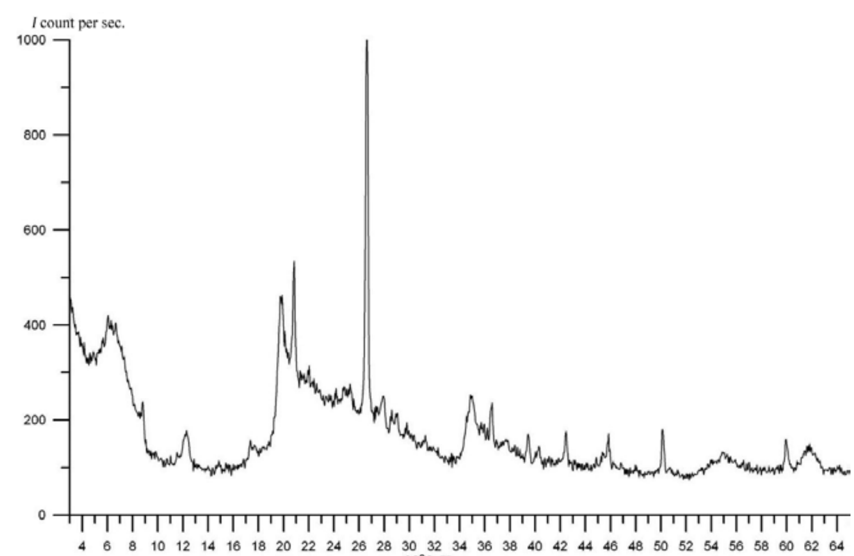


*Fig. 2. Radiographs of diatomaceous clay from Shadrinsky field.*

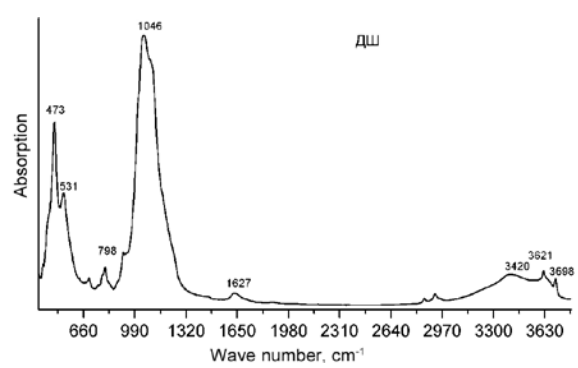


*Fig. 3. IR spectrum of diatomaceous clay from Shadrinsky field.*

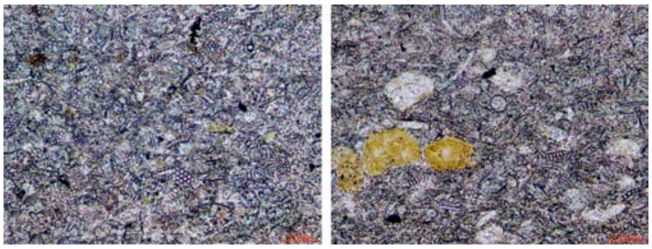

*Fig. 4. Microstructure of diatomaceous clay from Shadrinsky field.*

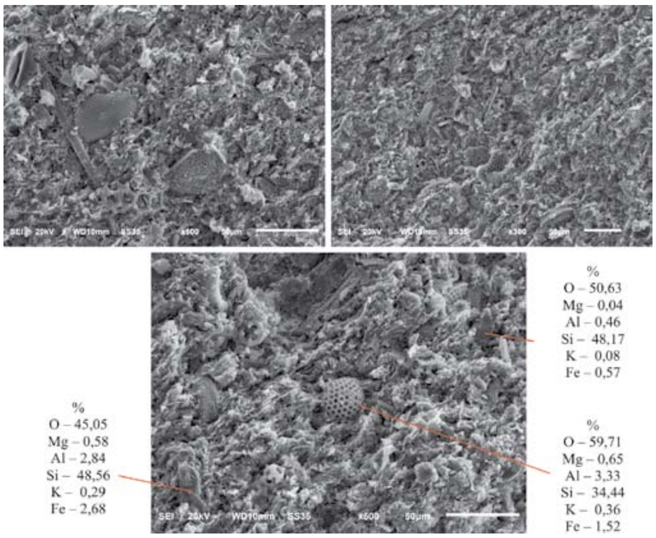


*Fig. 5. Microscopic structure and results of microprobe analysis of diatomaceous clay from Shadrinsky field.*

## Conclusions

The presence of characteristic biomorphic structure of the studied rocks allows us to characterize the rock as 'diatomaceous clay'. Diatomaceous clay of Shadrinsky field on the composition of the rock and quality of raw material is comparable to other fields of Trans-Urals. The main difference is the lower content of silica mineral phases, and large content of clay components. However, a significant argillization does not preclude their use in the production of building materials and thermal insulation; after heat treatment they can be used as an active additive in cement. Using diatomaceous clays in industries other than the construction involves more detailed studies of the physical properties of rocks, mineral composition, in particular of clay minerals and zeolites.

The Eocene diatomaceous clay of Shadrinsky field has signs of zeolite mineralization: studied rocks contain zeolites of calcium-sodium composition (up to a few %). It should be noted that the content of zeolite is much lower than in siliceous-carbonate sediments of the European part of Russia (Zorina, Afanasyeva, 2008; Zorina et al., 2008), and their origin is probably due to lithification and zeolitization of silicon gels at different stages of diagenesis.

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