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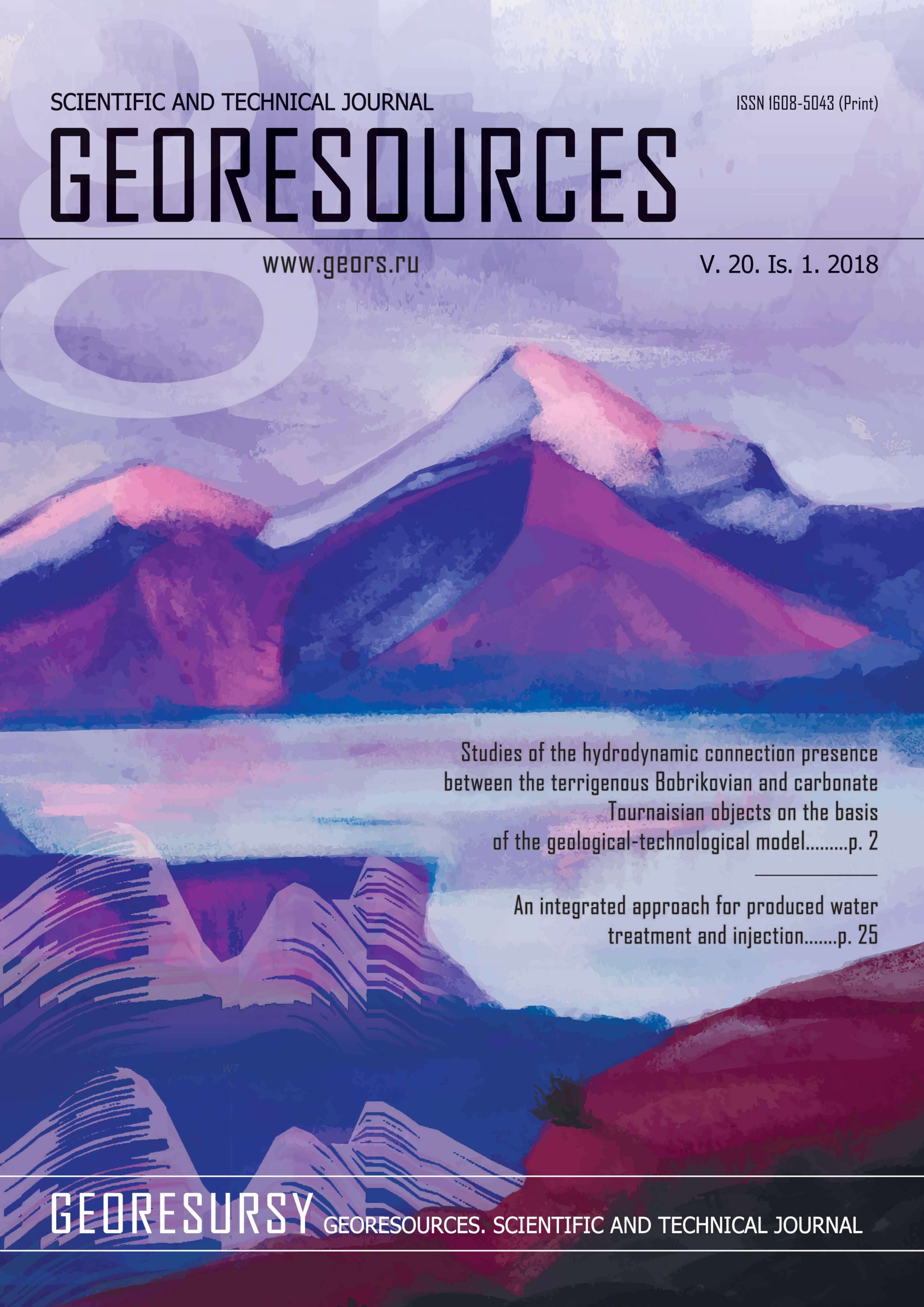

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ORIGINAL RESEARCH ARTICLE
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Studies of the hydrodynamic connection presence between the terrigenous Bobrikovian and carbonate Tournaisian objects on the basis of the geological-technological model of the site of the field

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Abstract. The authors suggest improvement of oil deposit development systems in Tournaisian and Radaevskian-Bobrikovian sediments in zones of erosion incisions with permeable types of reservoirs using the example of the Ashalchinsky oilfield.

Indicator studies were conducted in the experimental section of the Ashalchinsky field in 2014 to determine the hydrodynamic connection between the terrigenous Bobrikovian deposits and carbonate Tournaisian deposits. The presence of an indicator in the production well stock in the Radaevskian-Bobrikovian sediments inside the incision, when injected into the carbonate Tournaisian deposits over the side of the incision, indicates that there is hydrodynamic connection between the enclosing Tournaisian carbonates and the terrigenous Bobrikovian-Radaevskian formations that form the incisions. It follows that the filtration from the carbonate reservoir into the terrigenous, both laterally and vertically, occurs faster and more intensively when the terrigenous reservoir is imposed to the carbonate reservoir in the incision zone.

In order to confirm the presence of a hydrodynamic connection between the terrigenous Bobrikovian and carbonate Tournaisian objects, modeling studies were carried out to design the development of the site of the field. Based on the results of geological and technological modeling, it was revealed that the accumulated oil production from the wells of the Radaevskian-Bobrikovian production well stock may exceed the average well stock by 1-3 times.

Keywords: hydrodynamic connection, carbonate, terrigenous reservoirs, erosion incisions, oil recovery coefficient, indicator studies, fluorescein, filtration current lines

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In the Republic of Tatarstan, oil deposits in the Tournaisian sediments on all tectonic elements except for the outermost south-eastern part of the Oil and Gas Production Department Bavlyneft Tatneft PJSC area are more or less violated by erosion incisions. In this article, the authors consider complicated reservoirs filled with oil and disrupted by incisions, that is, oil deposits with such structure.

The enclosing rocks are the permeable carbonate rocks of the Tournaisian stage, and the filling rocks are terrigenous highly permeable sandy-siltstone formations of the Radaevskian-Bobrikovian horizon. In the zones of erosion of the Tournaisian deposits in the sections of the wells there are completely no clay formations of the Elkhovskian horizon. The reservoir of the Radaevskian-Bobrikovian age directly lies on the Tournaisian deposits.

The hydrodynamic connection between the enclosing and filling rocks, proved on the basis of instrumental studies, modeling and analysis of the technological performance of the wells, can be used in the design of deposits, including the arrangement of the project well stock, the development of geological and technical measures, taking into account the use of a highly permeable channel – naturally occurred incision, for a more effective development of oil reserves from weakly permeable Tournaisian reservoirs, organizing the displacement from them of oil into the higher incision channel[1] (Bazarevskaya et al., 2011).

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[1] Gubaydullin A.A., Bazarevskaya V.G., Yudintsev E.A. (2010). Geology of carbonate complex reservoirs of the Devonian and Carboniferous of Tatarstan. Report, Academy of Sciences, Kazan: FEN, 283 p.

Such a channel, carried out by terrigenous formations, can be used to improve technologies for the most complete development of oil reserves from weak permeable carbonate rocks in existing development systems[2]. At the same time, the oil recovery factor increases from low permeability carbonate rocks.

The existence of a hydrodynamic connection between the Carbonate deposits of the Tournaisian stage and sandy-siltstone deposits of the Radaevskian-Bobrikovian horizon has been contested so far by many scientists who maintain that the zone of erosion of the Tournaisian deposits is a stratigraphic and lithological screen (Khayretdinov N., Aminov L., etc.).

On the territory of Tatarstan, the most widespread erosion disturbances are observed on the eastern side of the Melekess depression[2] (Kozina, 1978). A striking example is the Ashalchinsky field, where, in fact, every uplift that controls oil deposits has been subjected to erosive disturbances of the sediments of the Elkhovskian horizon and the Tournaisian stage (Figure 1).

By the time of the deposition of terrigenous Tulskian formations, the incision is completely compensated and the structural plan on the bottom of the Tulskian stratigraphic object, as a rule, repeats the paleostructural plan of the Tournaisian stage (Figure 1). With the purpose of revealing the existence of the hydrodynamic connection in the Tournaisian and the Radaevskian-Bobrikovian deposits, we consider the results of the indicator injection and geological and hydrodynamic modeling on the example of one of the fields of the Republic of Tatarstan[3] (Salakhova, 2012).

1. Indicator studies

Indicator studies were conducted in the experimental section of the Ashalchinsky field in the pilot site in 2014 to determine the hydrodynamic connection between the terrigenous Bobrikovian deposits and carbonate Tournaisian deposits (Figure 2).

According to the results of the research, it was established that the concentration of the indicator in the flow of produced products and the time of its arrival to the production well depend not only on the filtration properties of the reservoir, but also on the current operating modes of the operating wells stock, that is why the investigations were carried out under steady-state operating conditions of the wells. Evidence are based on the results of determining the content of the eosin and fluorescein indices in the produced water of produced wells, located in the vicinity of the injection well No 4742, located outside the incision. Indicators were recorded in the well production samples in separate batches, which indicates the presence of

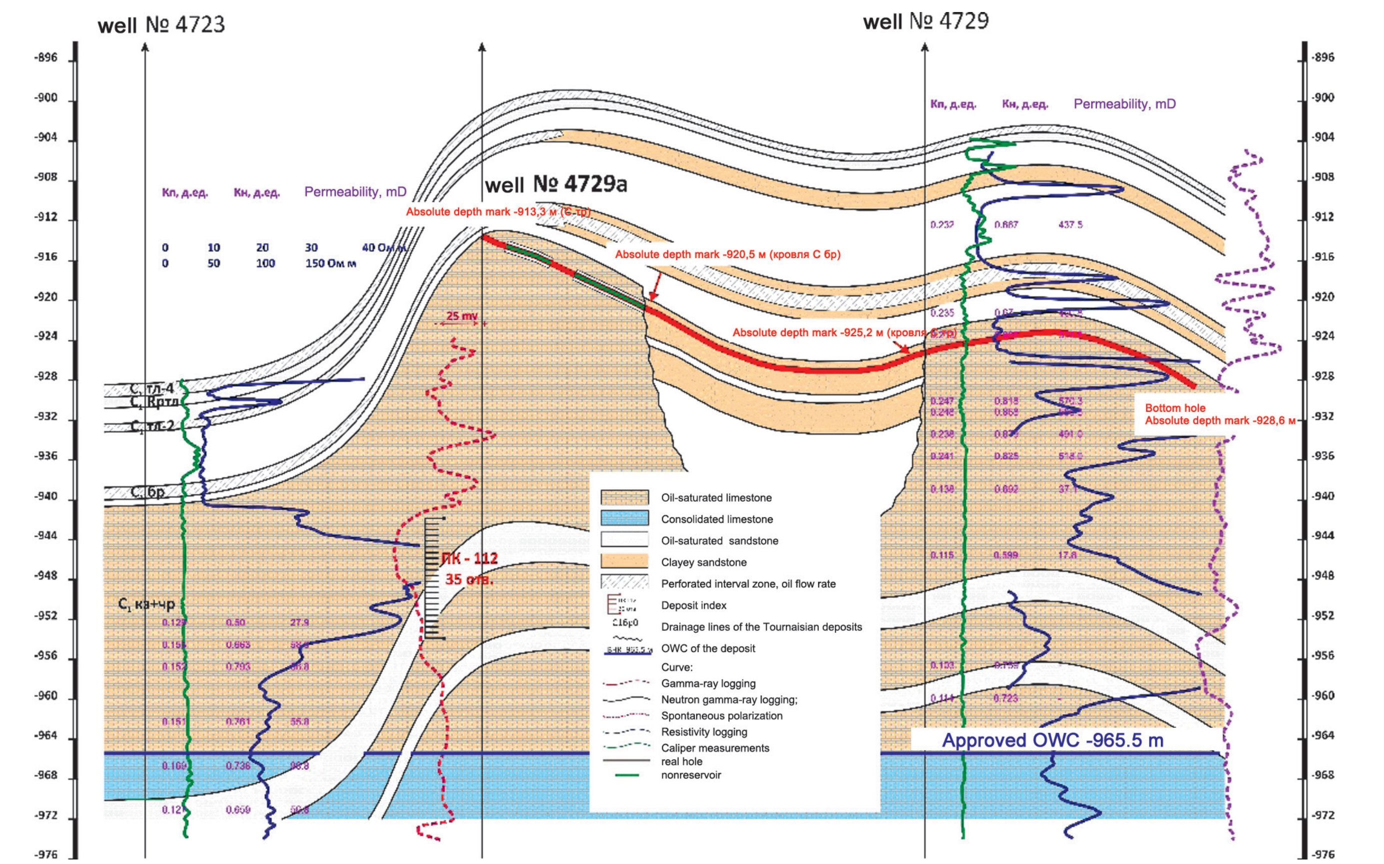

Figure 1. Compilation from the Lower Carboniferous section at the Ashalchinsky site of the Ashalchinsky field with the position of the actual trajectory of the horizontal section of the well trunk with horizontal end No 4729A

[2] Nureeva N.S. (2006). Technological scheme for the development of the Ashalchinsky oil field. Report. TatNIPIneft, Bugulma.
[3] Antonov G.P. et al. (2014). Investigations of the mutual influence of injection and production wells on the Tournaisian stage of the Ashalchinsky field by means of indicator studies. Report. LLC «Nauka», Bugulma.

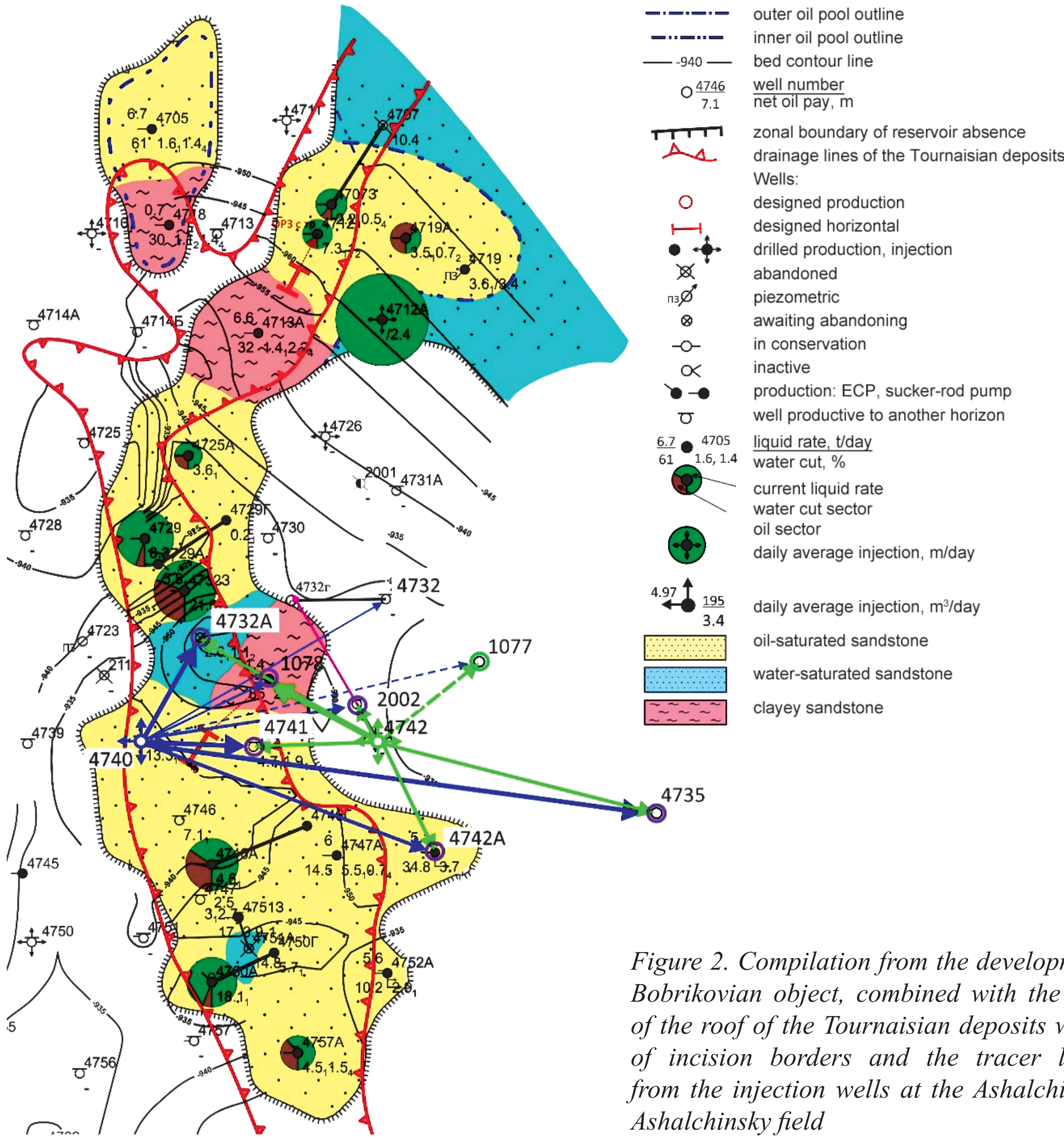

Figure 2. Compilation from the development map of the Bobrikovian object, combined with the structural map of the roof of the Tournaisian deposits with designation of incision borders and the tracer lines movement from the injection wells at the Ashalchinsky site of the Ashalchinsky field

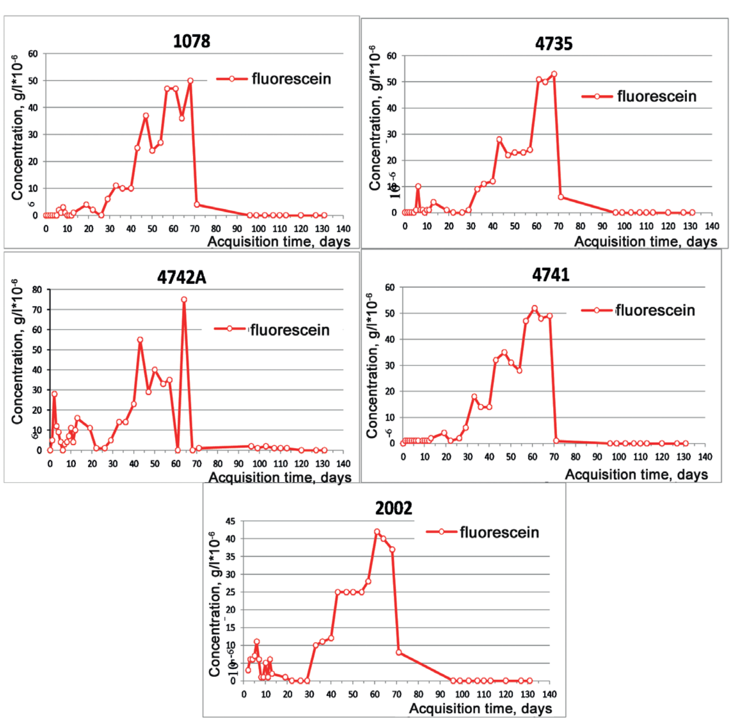

Figure 3. The dynamics of fluorescein release from the reservoir with some of the reacting surrounding wells

filter paths of different length and permeability, that is, high heterogeneity of the object (Figure 3). When interpreting the results of indicator studies, all geological, geophysical and fishery information was used: geological data, logging data, field data.

The identity in the time recording and concentration of the indicator in the surrounding producing wells on the maxima indicates the presence in the rock mass of the most permeable interlayers, regardless of their lithotype, and having a hydrodynamic connection during the path of filtration of labeled water from the injection to surrounding producing wells.

The presence of an indicator in the production stock of the reservoir in the Radaevskian-Bobrikovian sediments within the incision when injecting into the Tournaisian carbonate deposits outside the incision shows that there are hydrodynamic connections between the enclosing carbonates of the Tournaisian Stage (in well No. 4742) and filling terrigenous formations of the Bobrikovian-Radaevskian age. The relatively rapid appearance of an indicator in production of producing wells from high concentrations indicates that there are abnormally high permeable filtration channels in the formation.

A small fraction of the indicator extracted from the reservoir characterizes the low degree of influence of the injection well No 4742 to surrounding extracting plants, in which the fluorescein and eosin indicators are recorded. After the passage of the trailing edge of the labeled rim, the indicator in the adjacent produced waters of the surrounding wells was not recorded. It is possible that the main mass of the indicator has migrated to the lower-lying aquifers of the Tournaisian Stage, which are characterized by higher reservoir properties. The absence of an indicator in a number of producing wells indicates that there is no hydrodynamic connection of these wells with injection wells.

Thus, this proves that the filtration from the carbonate reservoir to the terrigenous one both laterally and vertically occurs faster and more intensively, when the terrigenous reservoir is superimposed on the carbonate reservoir within the incision zone[4].

2. Geological and hydrodynamic modeling

In order to confirm the existence of a hydrodynamic connection between the terrigenous Bobrikovian and carbonate Tournaisian objects, modeling studies were conducted to design the development of the field site. The calculated grid in the geologic-technological model of the oil deposit was 130 × 121 × 399 cells, further, a section with a calculated grid of 35 × 40 × 399 cells was cut out. Vertically, the objects were divided into a certain number of cells (Bobrikovian – 1 ÷ 10, Bobrikovian (incision) – 12 ÷ 193, Tournaisian – 194 ÷ 399).

The distribution of permeability, porosity and initial oil saturation along the site of the deposit (top view) for each of the objects is shown in Figures 4-6.

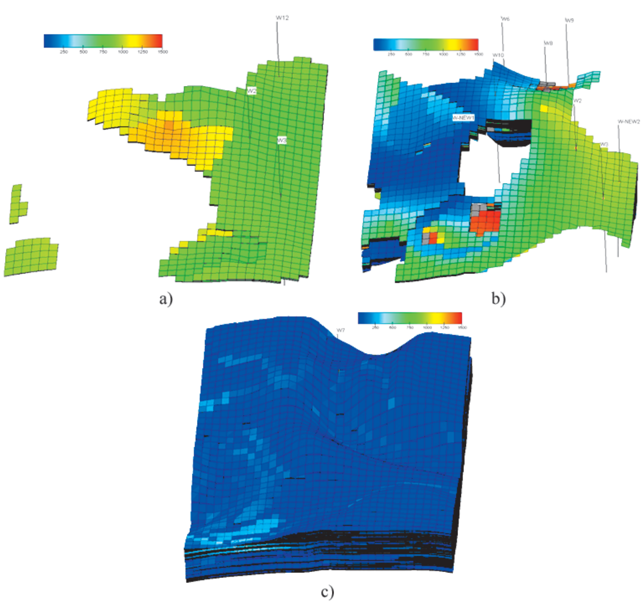

Figure 4. 3D distribution of permeability along the site of the field (top view) along the following objects: a) Bobrikovian, b) Bobrikovian-incision, c) Tournaisian

10 vertical wells are in operation in the area under consideration (w2, w3, w6, w7, w8, w9, w10, w12, w-new1, w-new2).

For the study, 2 options for further development of the reservoir section were considered: 1 – development without a system of reservoir pressure maintenance and 2 – with a system of reservoir pressure maintenance by pumping water into well w7 to the Tournaisian object for 15 years.

Analyzing the results of the hydrodynamic forecast calculations of the technological indicators of the site development and comparing the accumulated oil

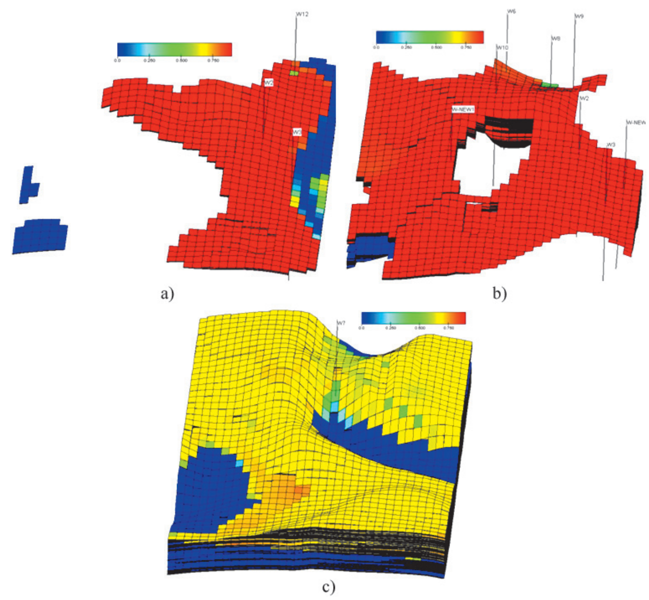

Figure 5. 3D distribution of the porosity along the field site (top view) along the following objects: a) Bobrikovian, b) Bobrikovian-incision, c) Tournaisian

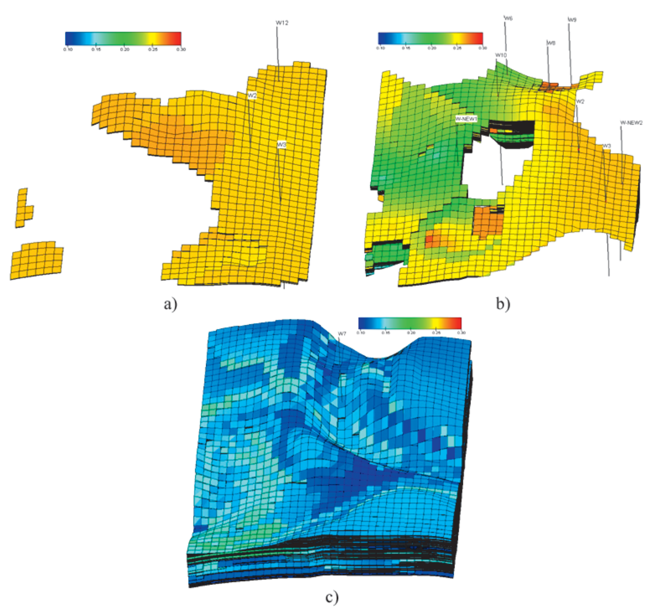

Figure 6. 3D distribution of the initial oil saturation along the field site (top view) along the following objects: a) Bobrikovian, b) Bobrikovian-incision, c) Tournaisian

[4] Monitoring of the use of horizontal technology at the fields of Tatneft PJSC. (2014). TatNIPIneft funds.

production, we find that, in the second variant, pumping water to the Tournaisian object leads to an increase in the accumulated oil production from the Bobrikovian object by 8,000 tons, i.e. part of the reservoirs from permeable carbonates of the Tournaisian object was displaced into highly permeable terrigenous rocks of the Bobrikovian-Radaevskian object.

A comparison of the accumulated oil production by the options for each production well of the site of the Bobrikovian object is shown in Figure 7.

The distribution of initial and final oil saturation in a section along the line of well 7 on the whole for the site of the plant according to the options is shown in Figures 8.

The distribution of initial and final oil saturation in a section along the line of well w7 separately for each object is shown in Figures 9,10.

In Figure 9b, it can be clearly seen that the injection of water into the well 7 leads to a change in the oil saturation in the Bobrikovian object. Comparing Figures 9 and 10, one can also notice a hydrodynamic connection between the Tournaisian and Bobrikovian objects.

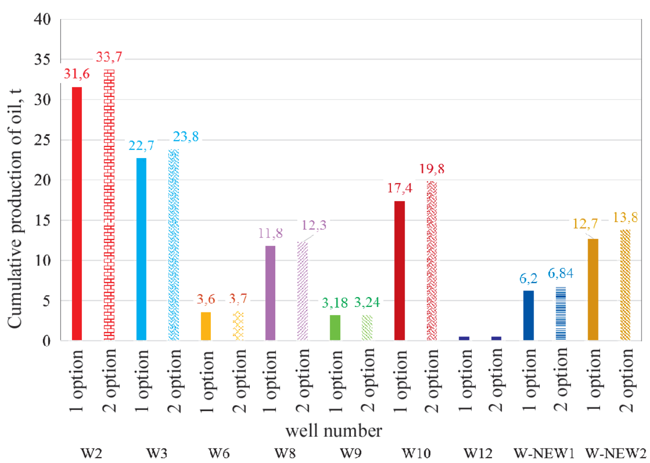

Figure 7. Comparison of cumulative production of oil wells according to options

In order to detail the process of the hydrodynamic connection of the Tournaisian and Bobrikovian objects, let us consider the filtration lines of the oil current for each variant.

The lines of the oil current to the producing wells of the considered deposit of the Bobrikovian object (incision) are shown in Figure 11.

Comparing Figures 11a and 11b, we can see that the injection of water into the well w7 of the Tournaisian object allows us to significantly change the current filtration lines in the area of wells that are perforated in the dome parts of the Bobrikovian (incision) object.

Conclusions

1. In erosion areas of Tournaisian deposits argillaceous formation of the Elkhovskian horizon are completely absent in wells. Reservoir of Radaevskian-Bobrikovian age directly overlies the deposits of the Tournaisian stage.

2. Rocks enclosing the incision are weakly permeable carbonate rocks of the Tournaisian stage; rocks filling the incision are clastic highly permeable sand and silt formation of the Radaevskian-Bobrikovian horizon.

3. On the basis of instrumental studies, geological-technological modeling and analysis of well production technology, the existence of a hydrodynamic connection between the enclosing rocks and rocks the incision has been proved.

4. Identification of hydrodynamic connection can be used to improve the development of the field, including the arrangement of the project well stock, selection of geological and technological measures, taking into account the use of highly permeable channel – incision – created by nature for more efficient highly production of oil from low permeable reservoirs of the Tournaisian stage, organizing the oil displacement into the highly permeable channel of the incision.

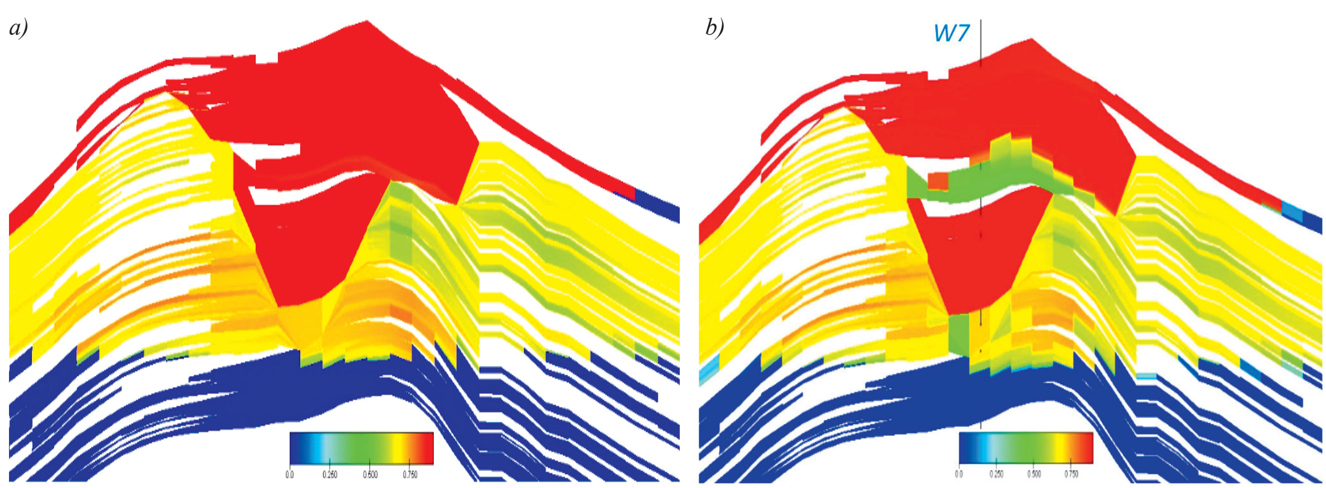

Figure 8. Distribution of oil saturation at the end of the forecast period in the section by options: a) 1 option without reservoir pressure maintenance, b) 2 option with reservoir pressure maintenance

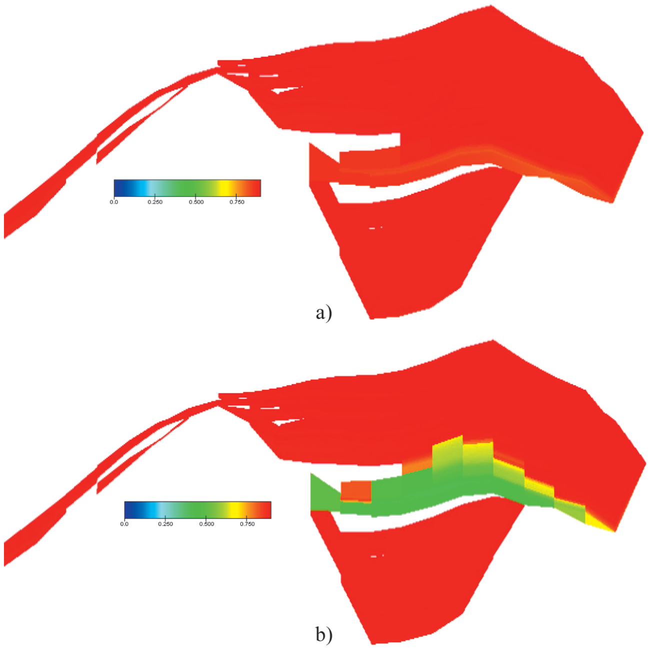

Figure 9. Distribution of oil saturation in the Bobrikovian object in the section by options: a) 1 option without reservoir pressure maintenance, b) 2 option with reservoir pressure maintenance

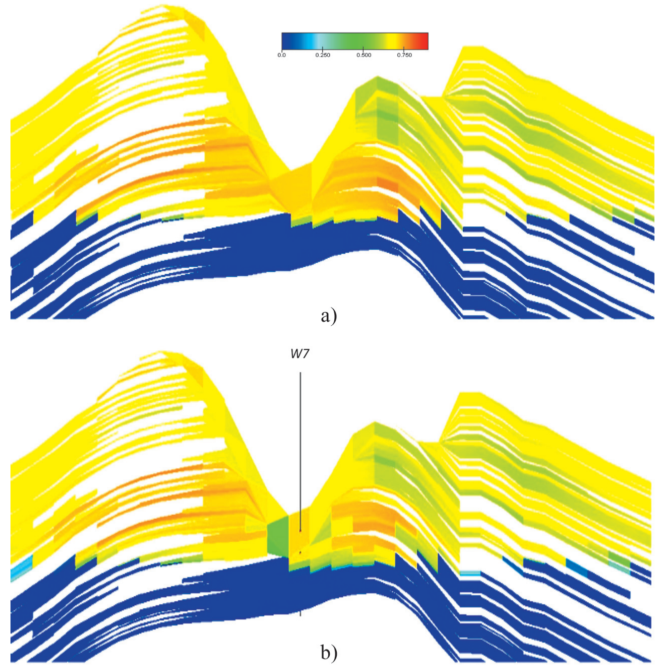

Figure 10. Distribution of oil saturation in the Tournaisian object in the section by options: a) 1 option without reservoir pressure maintenance, b) 2 option with reservoir pressure maintenance

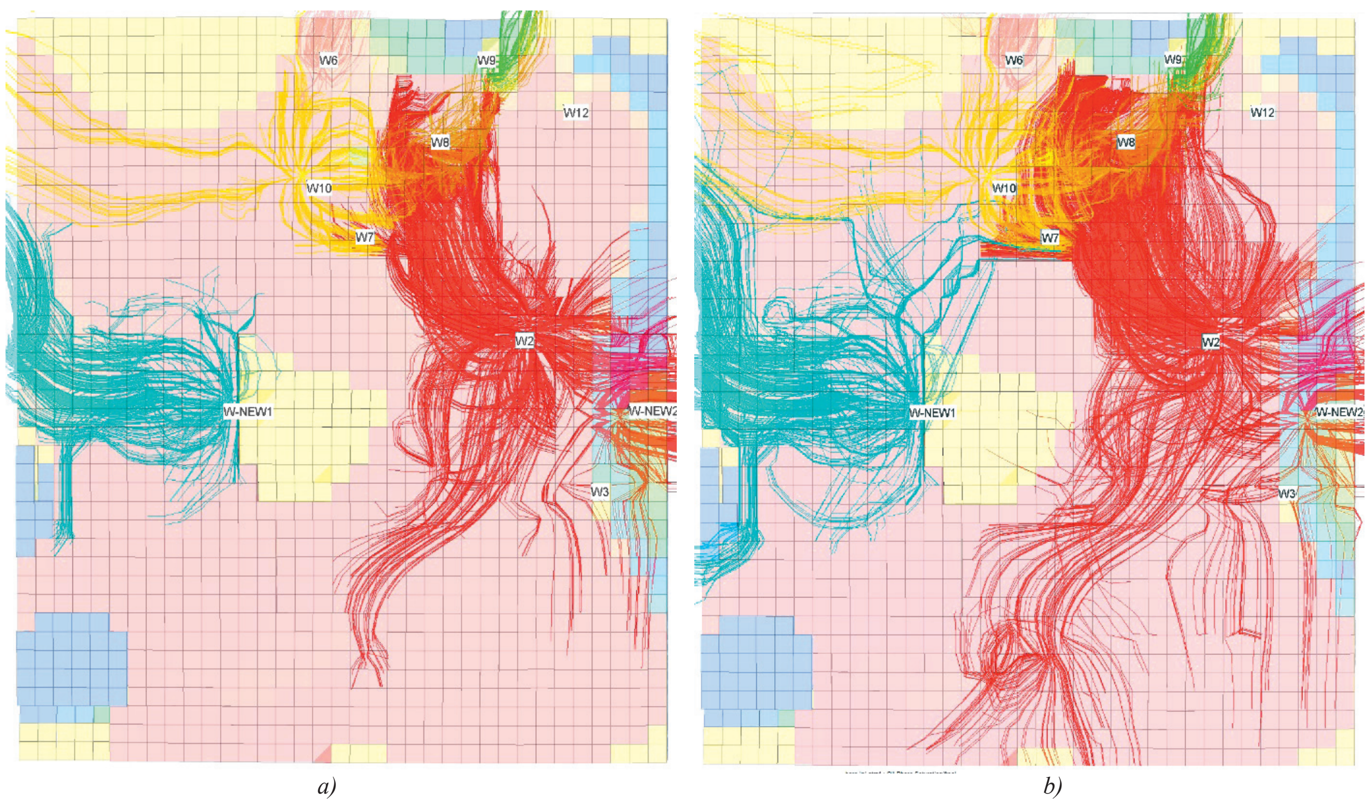

Figure 11. Filtration lines of oil flow in the Bobrikovian object (incision): a) 1 option without reservoir pressure maintenance, b) 2 option with reservoir pressure maintenance

5. By analyzing the technological performance of the wells and the results of geological and technological modeling, it was revealed that the accumulated oil production in the production stock of the Radaevskian-Bobrikovian object may exceed the average well stock by an average of 1-3 times.

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The use of technology of separating horizontal wells into sections by packers in conjunction with a new geological structure concept of deposits 302-302 of the Romashkino Field

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Abstract. The work considers deposits 302-303 of the Kuakbashsky area of the Romashkino oil field. The deposits 302-303 are confined to the carbonate layer of the Bashkirian and Serpukhovian sediments of the Middle and Lower Carboniferous, with various types of voids: intergranular, fractured and cavernous. Based on the analysis of seismic data, aerospace and geophysical data, a new model of the geological structure of deposits 302-303 was created, taking into account faults and lineaments. An analysis was made of the dynamics of horizontal wells operation, depending on the location of decompression zones, which confirmed the geological model of the deposit structure proposed by the authors. Based on the geological structure, solutions are proposed for optimization of deposits development:

- During the establishment and operation of wells, it is necessary to take into account the faults location, their type, strike, predicted locations of high fracturing and cavitation zones to improve well performance;
- The production mode should be developed with the obligatory observance of a balance between the filtration rate of oil from caverns into cracks and the flow of liquid from the production well.

The conducted analysis shows the complete absence of dependence of the development efficiency on the implementation of various technological measures. A comprehensive approach to the deposit blocks (limited by tectonic faults) is required, starting with the selection of the block (the direct drilling site), ending with the selection modes, sequence, type and complex of geological and technical measures, individually for each well of the block.

Keywords: deposits 302-303, Bashkirian and Serpukhovian stages, fracturing, faults, lineaments, oil production, water cut, porosity, permeability

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The study of carbonate deposits is of great importance for the development of the oil and gas industry on the territory of the Volga-Ural oil and gas province. It must be said that the Volga-Ural basin is the most studied of all provinces. In view of the fact that the terrigenous part of the sedimentary cover in the province has long been studied and virtually all the existing oil and gas fields are discovered and developed, and some are already depleted, further production of hydrocarbons in this area is primarily associated with carbonate deposits.

The deposits 302-303 of the Kuakbashsky area of the Romashkino oil field are confined to the carbonate layer of the Bashkirian and Serpukhovian sediments of the Middle and Lower Carboniferous, with various types of voids: intergranular, fractured and cavernous. Experimental operation of the deposit 303(represented by Serpukhovian sediments) was started in 1943; the deposit 302 (represented by the Bashkirian sediments) began to be operated from individual wells since 1957.

A large number of studies were carried out on deposits 302 and 303 to determine the causes of differences in production rates and differences in the intensity of water cut in neighboring wells, and methods for intensifying production and increasing oil recovery were tested. All the studies were based on the reservoir model of the deposits structure and by the present time it has not been possible to develop methods for increasing the development efficiency of deposits.

The authors proposed a new model of the structure of deposits 302-303 (Agafonov et al, 2014). According to this model, the Kuakbashsky swell, which controls

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deposits 302 and 303, should be divided along the structural-tectonic structure into three separate objects: Oikino-Altuninsky, Sortovodsko-Shugurovsky and Kuakbashsky (Figure 1). All these objects differ in origin and as a consequence in time of their formation. These differences also predetermine the differences in the distribution of fractures, since it is directly related to them. Oikino-Altuninsky uplift is formed by a reef core located in the Lower-Middle Famennian sediments, as it owes its origin to the external near-board zone of the Mukhanovo-Erokhovsky trough of the Kama-Kinel System. In the underlying structural levels this uplift is not manifested. Sortovodsko-Shugurovsky object is of a tectonic type and represents a block bounded from the west by one of the faults of the Altunino-Shunaksky trough, from three other sides by various faults, and the faults have different ages: sublatitudinal – Early Triassic or Jurassic, and submeridional – Kungurian and Kazanian. In this regard, the formation of fractures is completely different from the way diagenetic fractures are formed.

The Kuakbashsky object has a similar structure with Sortovodsko-Shugurovsky object; the difference is that the northern and eastern boundaries of the deposits within it are conditional and not associated with the zones of destruction. Thus, the southern part of the structure containing 302-303 deposits has sedimentary origin, while the central and the northern parts are of tectonic origin (Agafonov et al., 2014).

There are all kinds of stress sources on deposits 302-303. Tectonic disturbances are represented by several different-age and multidirectional fault systems, which are divided into inter-block and intra-block systems. Submeridional interblock faults were formed during the formation of the Pre-Urals fore deep in the Kungurian time and the Melekess depression in the Kazanian time. Fractures along the submeridional fault are closed. Sublatitudinal interblock faults and fracture zones accompanying them were formed during the deflection of the Caspian depression. Sublatitudinal faults continue to develop, as the deflection of the Caspian depression continues. This means that the fractures formed by these faults are still open and their healing with clay material continues (Figure 2).

At the present time, there is a diagonal system of geodynamic active zones of disturbances (GAZD). GAZD is a multi-rank regularly developed fracturing system formed by the rotational field of the Earth's stresses, caused by the need for periodic discharge of intracrustal stresses (Dragunov, 2011; Dragunov et al., 2017) with a direction of 65-155 degrees (+/-15 degrees), creating its fractured zones. Cavity passes through these

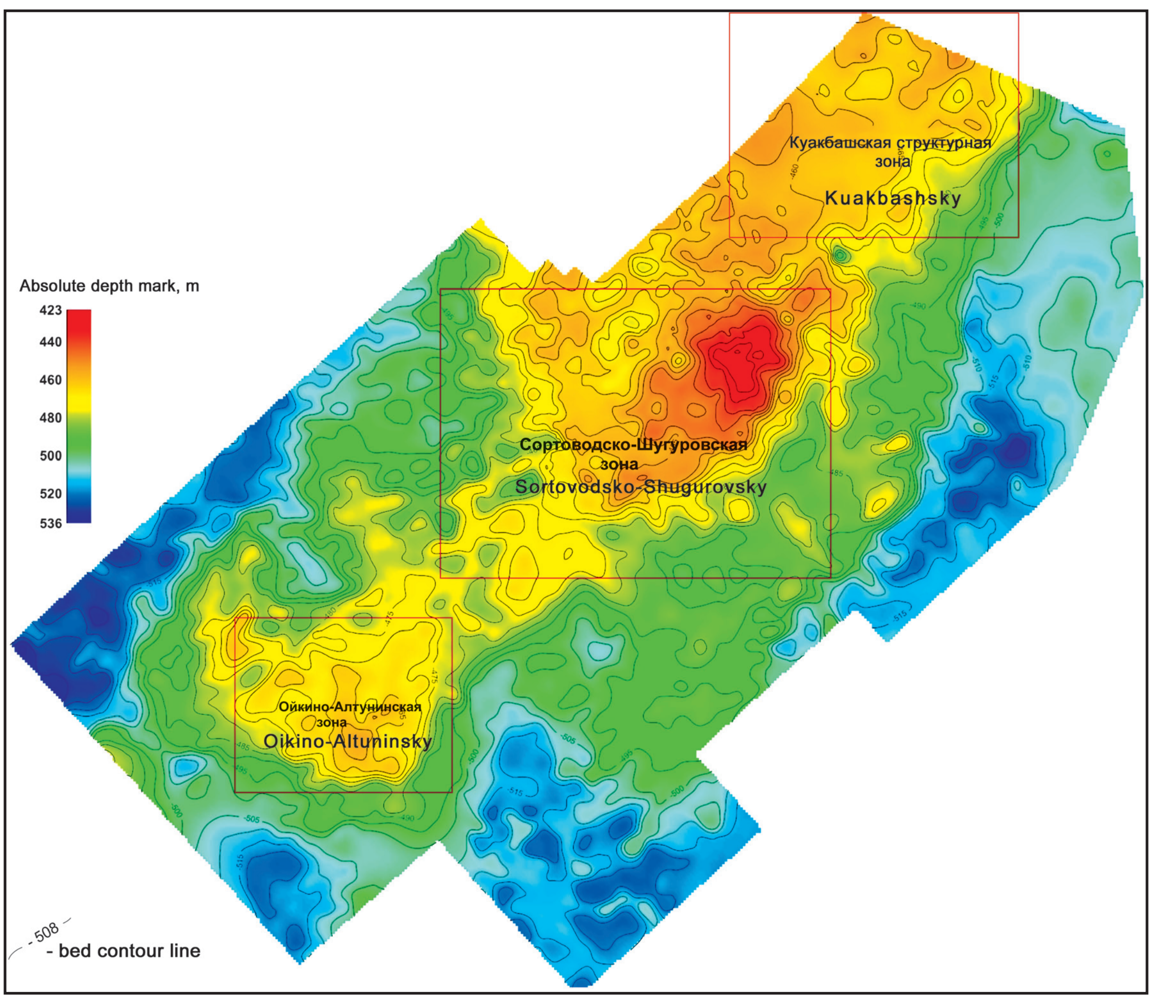


Figure 1. Structural map by the roof of the Middle Carboniferian horizon according to seismic data

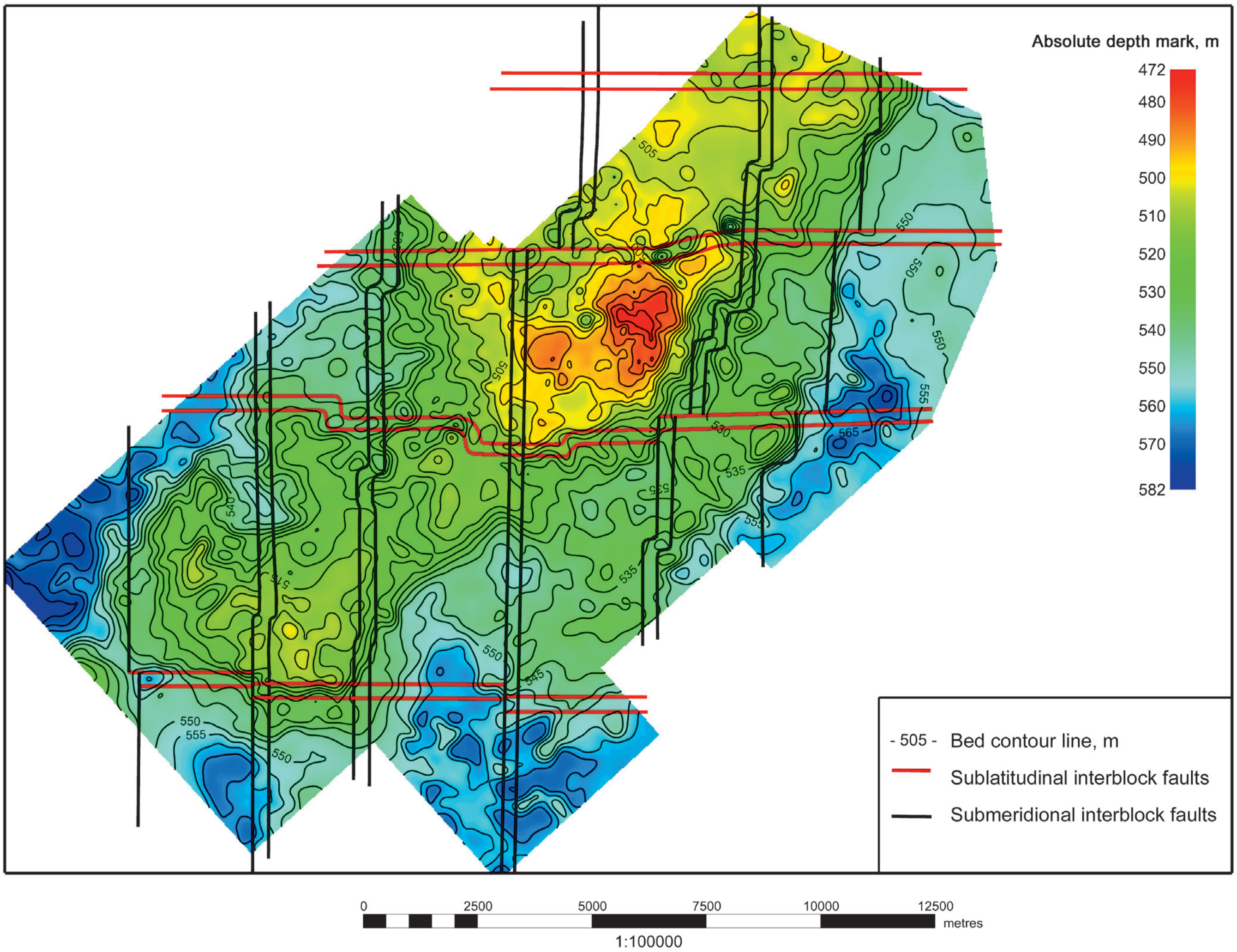


Figure 2. Structural map by the roof of Sbsh$_2$

fractures. Within the limits of all GAZD, and primarily of the zones of fluid flow (NW direction), tectonic fracturing is constantly in the active state.

In 2016 GPS and geological survey was carried out in the system-geodynamic modification over the entire area of deposits 302-303 with the purpose of distinguishing GAZD of different ranks (Figure 3). GAZD of the North-Western direction are the most active – distributive, and of the North-Eastern direction – cumulative[1].

The authors of the article have created a geological model of deposits 302-303 of the Romashkino field, taking into account tectonic faults and gas turbines, using the ROXAR software package (a package for geological modeling Irap RMS), which reflects the structure of the deposits as much as possible (Figure 4).

In most cases drilled wells on deposits 302-303 are quickly watered or enter into development with a high percentage of watercut.

In this paper, the geological structure of the deposits and horizontal wells is analyzed. The location of the well in relation to tectonic faults, lineaments (GAZD), as well as packers installed in the trunk is considered. The analysis was carried out in conjunction with development data to identify factors that affect the dynamics of horizontal wells.

A detailed analysis of two wells is given below, similar to the analysis of 25 horizontal wells drilled on these deposits.

Well No. 35387G is cased with a 114 mm shank equipped with packers "Kvart" in the intervals 951-952 m, 1034.5-1035.5 m, 1057.5-1058.5 m and a filter with magnesium plugs in the interval 1076-1096 m. The trunk of the well is directed to the marginal part of the GAZD of 7th rank with the NW direction. The sock of the borehole is closer to the bottom of Upper Bashkirian deposits. There are nine meters till oil-water contact; the formation is well cavernous with small densified areas (Figure 5).

There is a stable drop in oil production and a gradual increase in water cut. The rate of oil production falls for 20 months from 5.9 t/day to 2.2 t/day. The percentage of water logging for the first six months did not exceed 10%, gradually increasing – over the next 26 months it reached 30% (Figure 6).

[1]Dragunov A.A. (2016). Provedenie AKGI v sistemno-geodinamicheskoy modifikatsii po vsey ploshchadi rasprostraneniya zalezhey 302-303. Report. Kazan: TNG-Kazangeofizika LLC.

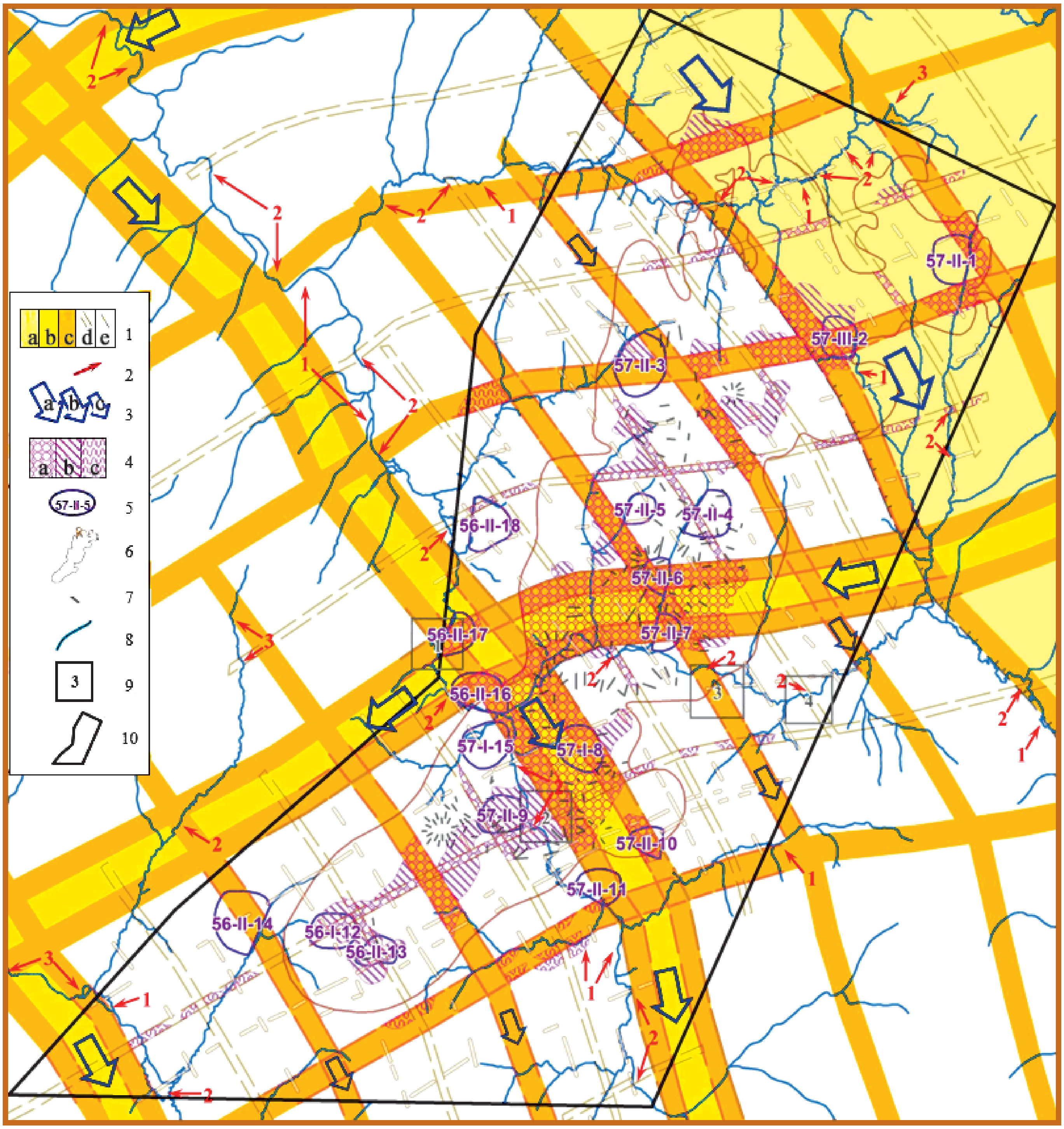


Figure 3. Map of the results of system-geodynamic modeling for the distribution area of deposits 302-303. Scale 1: 150 000.
1 – geodynamically active zone of disturbances (GAZD): a – 1-3d ranks, b – 4th rank, c – 5th rank, d – 6th rank, d – 7th rank;
2 – hydrological anomaly associated: 1 – with the gravitation of the water flow to the marginal parts of the GAZD, 2 – with the "П" -like "waste" of the river bed at its intersection with the GAZD, 3 – with a varied "refraction" of the river bed; 4 – with the bifurcation and wandering of the river bed at the site of its intersection with the GAZD and downstream;
3 – the expected flow of reservoir waters along the Serpukhovian-Bashkirian and lower-lying sediments, incl. on the basement: a – primary, b – secondary, c – third-rate;
4 – perspective object, associated with the multi-ranked framework of GAZD: a – within the GAZD, intersecting the geodynamically active uplift, b – on the periclinal of the large uplift, shielded by the GAZD; c – complicated, at the intersection point of the GAZD;
5 – cosmotectonic object, identified with the HC of the structural type and its number;
6 – the outline of the Kuakbashsky swell (based on the materials of Lukyanova R.G.);
7 – horizontal well;
8 – channel of a constant watercourse;
9 – reference section of system-geodynamic interpretation and its number;
10 – boundary of the distribution area of deposits 302-303.

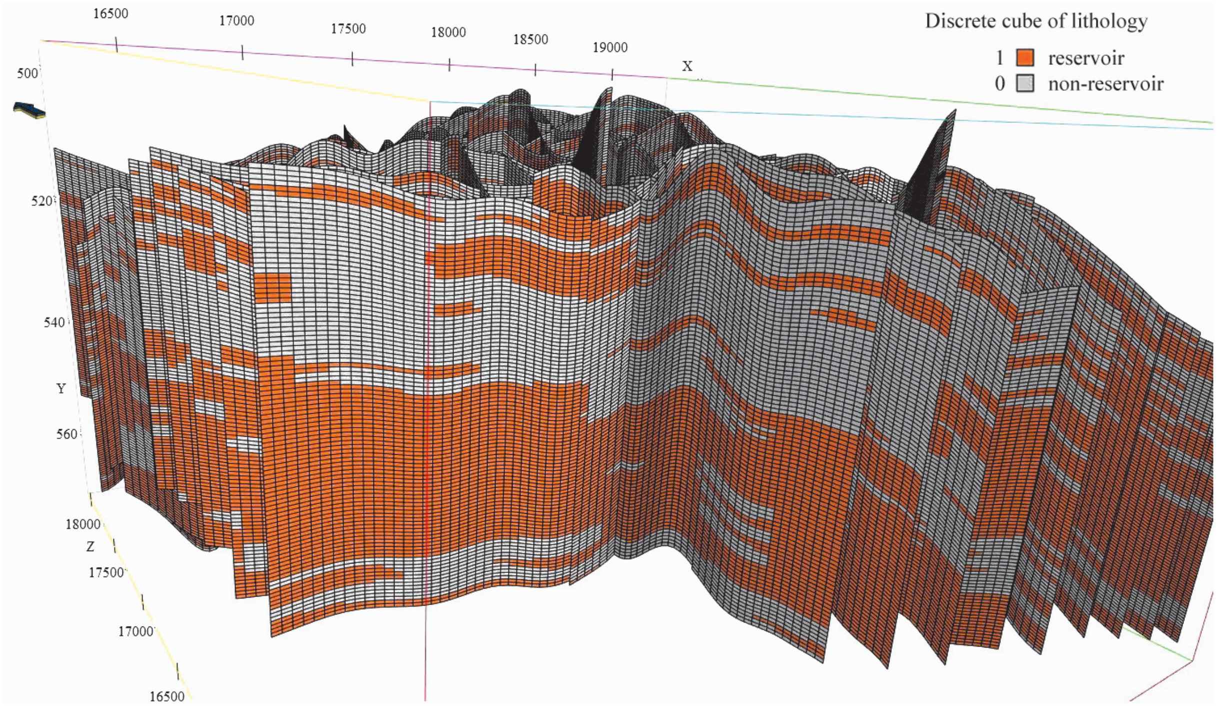
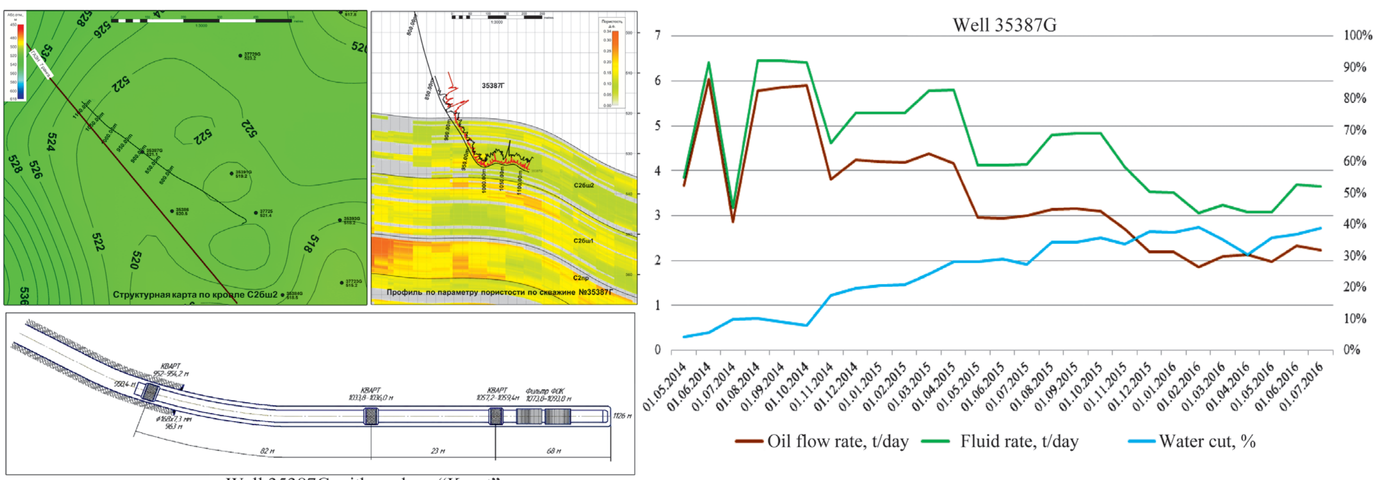
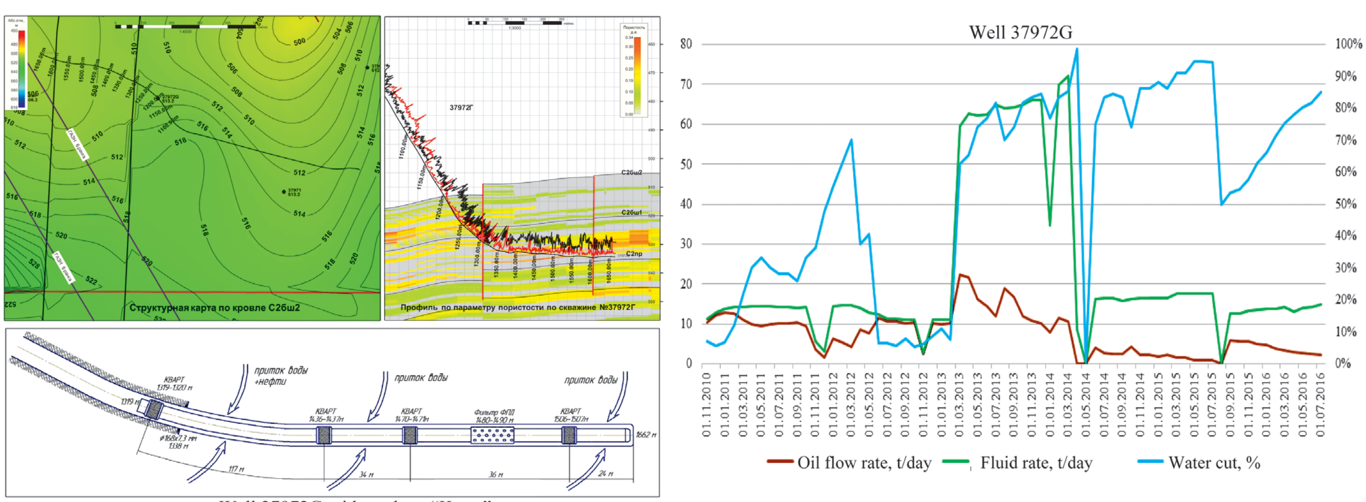


Figure 4. Distribution of the discrete lithological parameter of the geological model along the northern section



Well 35387G with packers "Kvart"

Figure 5. Well No. 35387G



Well 37972G with packers "Kvart"

Figure 6. Well No. 37972G

Watering is low and slowly growing, possibly due to the fact that the well does not cross the sublatitudinal interblock fault with open fractures and does not cross the GAZD. The extraction is conducted not from fractures, but from caverns, which feed GAZD of the seventh rank with the NW direction, the border zone of which is located 40 meters from the perforation interval.

From the packer in the interval 1057.5-1058.5 m the effect was minimal; there was no need to cover this interval.

Well No. 35387G is an example of a well that has been successfully drilled. The trunk does not cross faults; it is drilled in the Upper Bashkirian deposits (denser carbonates). The well works stably with a small oil production rate, without a rapid increase in water supply, the barrel is directed to the border zone of GAZD of the 7th rank with the NW direction, from which the solution for cavity formation was given (Figure 6).

A 114 mm casing liner with packers "Kvart" was installed in the horizontal well trunk No. 37972G in the intervals 1507-1506 m, 1471-1470 m, 1437-1436 m, 1319-1320 m and a filter in the interval 1480-1490 m.

The well trunk is located at some distance from the sublatitudinal interblock fault with open fractures and crosses two interblock submeridional faults with closed fractures. Also, the sock of the well is located in the immediate vicinity of the marginal zone of GAZD of the 6th rank with the NW direction. The sock is located in the Lower Bashkirian sediments. There are nine meters to the oil-water contact; the reservoir is medium-sized in the Upper Bashkirian sediments, mediumly cavernous with compacted areas in the Lower Bashkirian sediments (Figure 6).

In the first eight months, the percentage of water cut reached a value of 68%, after the remedial cementing the percentage of water cut sharply drops first to 47%, after – up to 6%. After the next two months, the flow rate of the liquid increases sharply to 60 m^3/day, and within six months the percentage of water cut reaches 98%. In May 2014, the shank with packers is lowered, the interval is 1481.6-1491.7 m, a filter (1480-1490 m) is installed and extraction is conducted. Reducing the selection of liquids to 17 m^3/day, watering is reduced to 81%, for eight months the water supply reaches 93%. In August 2015, waterproofing works are carried out and the extraction of liquids was reduced to 12 m^3/ day, which allowed reducing the water supply to 52% (Figure 6).

A good interval for perforation is chosen – it is located 270 meters from the GASD boundary of the 6th rank with the NW direction. From below (1506-1507 m) and from above (1470-1471 m), the perforation interval was isolated by packers. The effect of the packer established in the interval (1470-1471 m) is absent, and in the lower interval it is expedient to install the packer, since in the toe the well trunk and the GASD practically intersect. The packer in the range of 1506-1507 m is installed in an insufficiently dense part and therefore the water has come quickly, waterproofing works allow closing the washed fractures and lowering the water cut, due to the activation of the unwashed ones, but the effect lasts not for long for two reasons: first, the gel breaks and closed fractures again become permeable, and secondly, new cavern fractures are washed to already flooded vertical fractures

As a result of the work, a new geological model was created and the dynamics of the operation of horizontal wells was analyzed in coordination with geology, on the basis of which the following conclusions were made:

- During the establishment and operation of wells, it is necessary to take into account the faults location, their type, strike, predicted locations of high fracturing and cavitation zones to improve well performance.
- The production mode should be developed with the obligatory observance of a balance between the filtration rate of oil from caverns into cracks and the flow of liquid from the production well.
- The conducted analysis shows the complete absence of dependence of the development efficiency on the implementation of various technological measures: the location of the well relative to the faults, the placement of packers, plugs and filters, perforation intervals, water shutoff treatment, change in extractions and depressions A comprehensive approach to the deposit blocks (limited by tectonic faults) is required, starting with the selection of the block (the direct drilling site), ending with the selection modes, sequence, type and complex of geological and technical measures, individually for each well of the block.

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Regional study is the next important stage in evaluation of oil and gas industry potential of sedimentary basins of Western Kazakhstan

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Abstract. The article presents the general state of exploration and regional geotectonic characteristics of the structure of the basins of Western Kazakhstan (the Caspian Basin, Ustyurt-Bozashi and Mangyshlak). Principal results of regional studies carried out on the «Comprehensive study of sedimentary basins of the Republic of Kazakhstan» project for 2009-2013 are given. Based on this, topical issues in the study of the deep structure of basins are emphasized, from the perspective of further assessment of the forecasted hydrocarbon potential.

In accordance with the new deep drilling data (5.5-7.0 km and more) in recent years, the importance and necessity of specifying the structure and high prospects of the Paleozoic deposits are substantiated. In this regard, it is stated that it is advisable to post a parametric well in the future with an anomalous projected depth (14-15 km) in the central part of the Caspian Basin (Eurasia Project). Also, the program of regional studies (geotraverses and 2D seismic profiles) on the most important geological «cuttings» from the sides of the Caspian basin to the center, the zones of its articulation with the other basins that apply in the south, was considered. The characteristic of the problems solved by the program of regional study of the basins of Western Kazakhstan is given.

Keywords: basin, depth, oil and gas content, drilling, seismic studies, study, Paleozoic deposits, West Kazakhstan, Caspian basin, Ustyurt-Bozashi, Mangyshlak, geophysical anomalies, West Turan plate, oil and gas prospects

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State of exploration, results of previous years and landmarks

Sedimentary basins of Western Kazakhstan in the Caspian region (the Pre-Caspian, Ustyurt-Bozashi, Mangyshlak) concentrate almost all significant deposits and facilities that ensure the fulfillment of planned targets for oil production. The development strategy of the Republic of Kazakhstan envisages the increase of oil production by 2020 to 100-120 million tons per year, which is 1.5 times higher than the current production level. At the same time, the expansion of oil production is mainly due to the giant and large Paleozoic deposits of the Caspian region (Tengiz, Karachaganak, Kashagan and Zhanazhol groups, Uzen, Kalamkas, Zhetibai, and Imashevsky) geotectonically related to the Caspian basin and the west of the Turan plate.

The high capabilities of the most significant, three domestic "giants" (Tengiz, Karachaganak, Kashagan) nevertheless cannot fail to take into account one of the main factors of the high content of sulfur elements in oil and gas (hydrogen sulphide, mercaptan, etc.). This, to our knowledge, is associated with the strengthening of ecological pressure on the environment and increasing the corresponding requirements for exploratory wells and development of new promising areas and deposits. Meanwhile, the gradual depletion of the existing reserves makes it increasingly necessary to replenish the mineral and raw materials complex with new reserves. Taking into account the planned production levels, the annual increment of recoverable reserves, optimal for replenishment of the extinguished reserves, is estimated at about 100 million tons or more for the future.

In total there are about 280 hydrocarbon fields in the territory of Kazakhstan, located within six oil and gas basins (the Caspian Sea, Mangyshlak, Ustyurt-Bozashi, Shu-Sarysu, Yuzhno-Torgai, and Zaisan Basins) with a total recoverable reserves of industrial categories of

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about 5.5 billion tons of oil and 3.0 trillion m[3] of free and dissolved gas (Figure 1). Of the total, 233 fields have been discovered in the Caspian region, including 8 in the water area of the Northern and Middle Caspian. Of these, 162 fields have been discovered in the Caspian Basin, 55 in Mangyshlak and 18 in Ustyurt-Bozashi. In general, despite this, further sustained economic growth and the development of the oil and gas industry require the expansion of the resource base for hydrocarbon resources on shore and off-shore, which requires studies on further assessment of new opportunities within the existing oil and gas basins and prospective oil and gas basins of Kazakhstan.

The outlined early delay in the planned replenishment of the hydrocarbon potential and the timely preparation of conditioning facilities for drilling was a consequence of the lack of systematic study of sedimentary basins during the last 20 years. The research of the structure and prospects of the territories for objective reasons was unplanned and fragmented. The works were carried out, mainly, on separate local sites and contract territories and, as a rule, near areas with known and developed hydrocarbon fields and developed infrastructure.

Simultaneously, in the period from 1991 a significant amount of new geological and geophysical information was accumulated, which did not receive timely and comprehensive analysis. As a result, this affected the quality and success of geological exploration, which, in turn, restrained a reasonable increase in the volume of forecasted resources, increment of reserves, and discovery of new hydrocarbon fields. In these conditions, it is necessary to increase the geological exploration volumes with an emphasis on the discovery of large hydrocarbon fields in the most studied areas, especially in the Caspian region, which has been studied best with respect to modern research methods. This region contains all the most significant hydrocarbon fields, and therefore, the effective further economic development of the sector involves carrying out explorations in the most promising significant areas related to new discoveries in the Paleozoic deposits, capable of replenishing the hydrocarbon material resource base in a multiple and short timeframe (Karabalin, Iskaziyev, Azhgaliev, 2013).

Under these conditions, at the initiative of the Committee for Geology and Subsoil Use of the Ministry of Industry and Energy of the Republic of Kazakhstan (hereinafter referred to as CGSU) and KazMunaiGas NC (hereinafter – KMG) for the period of 2009-2013 the **"Comprehensive study of sedimentary basins of the Republic of Kazakhstan" (CSSB RK) project was carried out**. These studies on such a wide scale were carried out for the first time and undoubtedly are the first experience in carrying out a comprehensive geological study and assessing the prospects of large areas across all 15 sedimentary basins of the country. The main argument and basis for the formulation of such studies was the lack of systematic, consistent, and integrated study of promising areas and sedimentary basins.

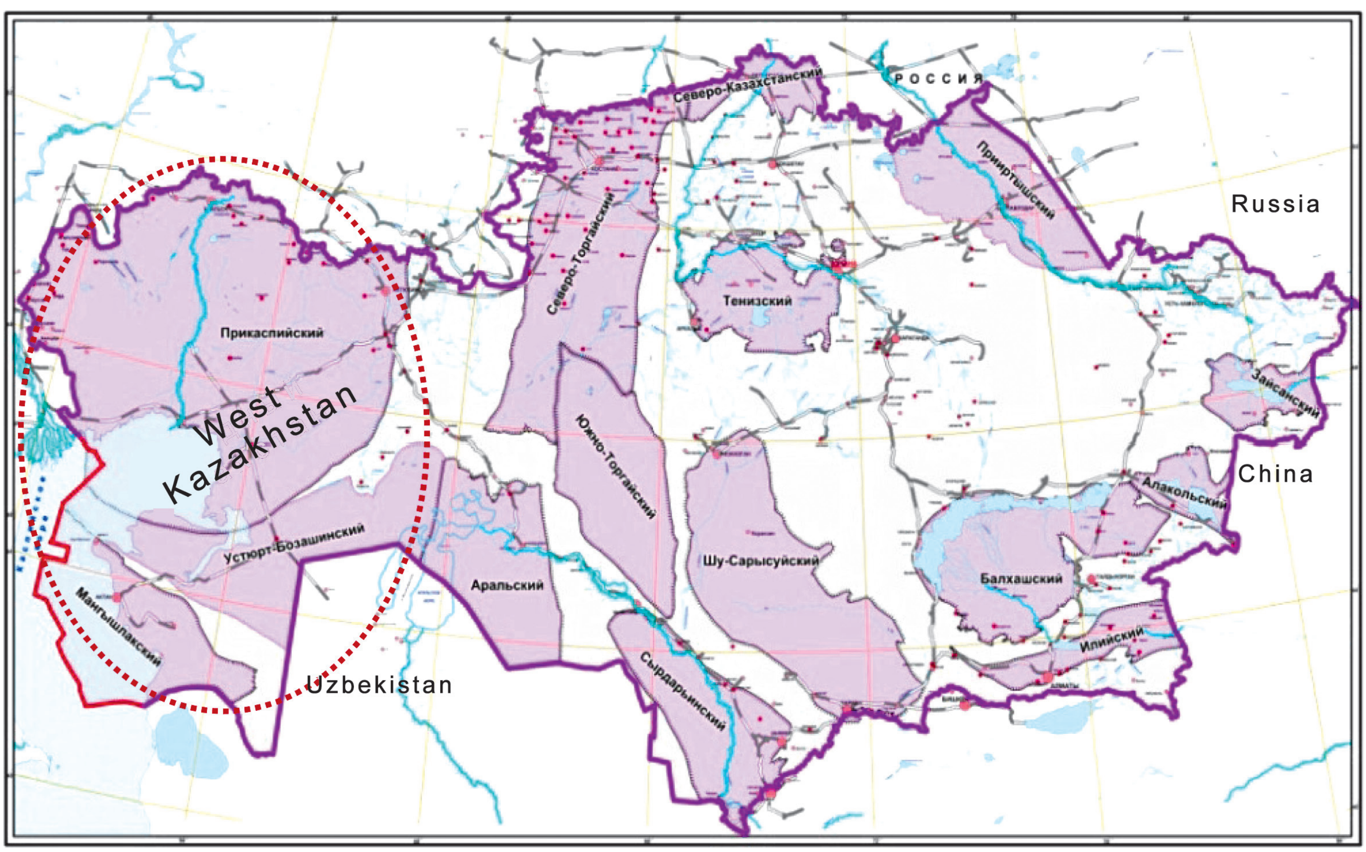

Figure 1. Scheme of sedimentary basins of the Republic of Kazakhstan (according to U.A. Akchulakov et al., 2009-2013)

Significantly increased technical capabilities and a qualitatively new level of data processing and interpretation were important arguments in assessing opportunities and justifying the ultra-deep well in the central part of the largest major promising Caspian Basin under the new regional Eurasia Project (Kuandykov, Volozh, 2015). Under these conditions, there is every reason to expect a high efficiency of research aimed at clarifying the concept of a section and a deep model of the structure of the Caspian Sea. Without a doubt, in this case, research should be coupled with the most detailed analysis and study of materials.

Traditionally, as known, there are two methods of studying oil and gas bearing structures: drilling and seismic exploration. At the same time in the Soviet era, the most important role was assigned to the integration of methods, which predetermined the stage and systemic nature of the preparation and justification of local search facilities. Taking into account the key research methods (gravimetric and aeromagnetic survey, electrical prospecting, geochemical studies, etc.), the preparation of structures from the regional stage to detailed work was more or less clearly monitored. By the combination of this large multi-stage work, a fund of prioritized and most prepared facilities was formed, and the possibilities of opening new fields and deposits were planned.

At the modern "transition" stage, the volume of research on the integration of methods has been sharply reduced. Accordingly, the effectiveness of prospecting and exploration has decreased significantly. Even in spite of the great prospects, marked by the results of the Comprehensive Study of the Sedimentary Basins of the Republic of Kazakhstan, the number of new discoveries has sharply decreased. If according to the statistics of the "pre-perestroika" period of work, an average of 2-3 fields were discovered each year with a fairly acceptable estimate of the recoverable reserves, now a decade is needed for their discovery. Thus, on the territory of activity of KMG as a whole in the period of 1999-2017 positive results were obtained (excluding the off-shore area) in 4 cases. However, given the quality and conditionality of the preparation of search facilities and the low assessment of these facilities in terms of reserves, which can be regarded as closely related factors, these discoveries can not be considered quite acceptable and cost-effective.

Therefore, based on the results of the Comprehensive Study of Sedimentary Basins of the Republic of Kazakhstan, the main program documents for the development of the mineral and raw materials complex have been adopted for the sectoral program of the CGSU for geological exploration for 2015-2019 and the Program of long-term development and replenishment of hydrocarbon reserves of KMG for the period up to 2020. They set the goal of forecasting the oil and gas potential of new territories and expanding the resource potential by conducting a significant amount of prospecting work. One of the important reference points is the increasing depth of research and conducting prospecting at elevated depths (5.5-8.0 km), mainly associated with Paleozoic deposits.

As the studies and data of the last quantitative assessment for 2009-2013 have shown[1], the Paleozoic sediment complex is the main research interval in a section that concentrates almost the entire volume of identified hydrocarbon reserves. In particular, the potential for the forecasted resources of categories D_1 and D_2 is very significant in this assessment. Within the Caspian region, the potential of the basin of the Caspian Basin for geological and recoverable resources is an order of magnitude greater than that of the rest of Kazakhstan, mainly due to Paleozoic deposits. Therefore, the updated quantitative assessment of the forecasted resources, which clarifies the prospects of oil and gas content, the directions for further prospecting and exploration, and the placement of research volumes are the main results of the integrated study of the basins.

Previously known and open giant and large reserves of hydrocarbon deposits in the Paleozoic complex are confined to the flanks of the Caspian basin at depths of up to 5.0 km in deposits of predominantly carbonate composition containing sulfur and hydrogen sulphide at elevated concentrations. In the relatively inland basin part, mainly smaller and insignificant hydrocarbon deposits are found. In recent years, data on the petroleum potential of Paleozoic deposits at depths of 6.0-7.0 km and more have been obtained. The technical level of processing and interpretation of geological and geophysical data (drilling and seismic data) and information on the composition of oil and gas-bearing strata and samples of gas, condensate and formation fluids has significantly increased. This makes it possible to highly estimate the prospects for the discovery of new large-scale hydrocarbon deposits throughout the Caspian Basin, including in the internal relatively submerged areas associated with terrigenous and carbonate-terrigenous sedimentation, favorable for operations, primarily in environmental terms .

In the context of the Ustyurt-Bozashi and Mangyshlak basins, the state of the Paleozoic complex has been studied at the initial stage. At the same time, deposits of industrial significance (Oymash, Karakuduk, Karachalak, Urga and others) were found in some areas in the Paleozoic and favorable conditions allow us to outline and justify the high prospects of Paleozoic deposits in the context of these basins. Despite one

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of the serious objective factors, there is a lack of data completeness and very poor drilling of the lower part of the section (Paleozoic) of the western part of the Turan plate (Ustyurt-Bozashi and Mangyshlak).

As noted above, in the long term, a significant part of the resources will be represented by hydrogen sulfide-containing subsalt deposits of the Caspian Basin, which will be associated with significant costs of oil refining and the use of equipment with high corrosion protection, as well as increasing environmental pressure on the environment. This is clearly demonstrated by the initial stage of the development of Kashagan. KMG and its partner companies are faced with a high degree of risk and, accordingly, the complexity of implementing the ultimate strategic goal of increasing the production volumes in a short time, traditionally due to deposits with a carbonate composition of reservoirs containing hydrogen sulphide and sulfur at elevated concentrations.

One of the effective and alternative directions of work in these conditions for replenishing the mineral resources sector is the search for and discovery of new large low-sulfur deposits in terrigenous and carbonate-terrigenous deposits, characterized by more favorable conditions of occurrence, which are safe for subsequent development in an ecological sense, since the expansion of the resource base through the search and exploration of new hydrocarbon fields is a key task of the country's oil and gas industry at present.

In comparison with the rest of Kazakhstan's perspective oil and gas bearing territory and in accordance with historical approaches and assessments, the whole territory of the Caspian region in Western Kazakhstan is the most studied, especially in the upper Mesozoic-Nosenian and partly sub-Paleozoic part of the Caspian basin section. At the same time, due to the data on the oil and gas content of the Paleozoic of the Caspian Sea at great depths, the increased level of data processing and interpretation, the possibilities of analysis and construction of volumetric three-dimensional models and basin modeling (within the framework of new methodological "approaches"), the assessment of the potential of the Paleozoic complex of the Caspian region was conducted to the full extent and in joint stance.

Earlier, the Paleozoic complex was relatively studied in local areas of the Caspian Basin mainly in the flank areas at depths accessible for drilling (Figure 2). In the inland regions, the study of drilling is much lower. With the appearance of new data on the Paleozoic productivity at depths of 6.0-7.5 km in recent years (2010-2015), the views on the conditions of occurrence and prospects of the oil and gas potential of this complex on the territory of all basins within the Caspian region are largely updated. Although in the flank zones of the Caspian basin the study of drilling and seismic prospecting is relatively high, mainly due to the concentration of studies in individual local areas, the basin area in this respect remains practically unexplored[1] (Kuandykov, Volozh, 2015).

In general, the area promising in the oil and gas terms within the Caspian, Mangyshlak and Ustyurt-Bozashi basins has been expanded to a considerable extent. Thus, the territories of Mangyshlak and Ustyurt-Bozashi for the Paleozoic complex are included for the first time in the category of prospective ones, and also part of the Paleozoic section of the Caspian basin that is involved in the assessment and justified for this is below -7.0 km label[1] (Karabalin et al., 2013). Accordingly, the quantitative assessment has largely been improved by shifting the areas of research to the inner and central areas of the Caspian Basin and most of the off-shore of the Northern and Middle Caspian. As a result, and in accordance with the structural-tectonic zonation, prospective exploration blocks are identified with a preliminary assessment of the prospects in their composition of individual detailed priority areas and facilities.

According to the results of high-precision aerial magnetometer survey performed within the framework of the KGaS RK Project, for the first time a preliminary scheme of a magnetic active surface (1:2000000) was prepared for western Kazakhstan, which is tied to the distribution areas of high magnetization of the basement rocks, which characterizes the behavior of the distinguished conditional surface[1] (Kiinov et al., 2014). At the same time, it allows to differentiate the territory into separate elements, to link the mutual location of large zones, and to clarify the nature of their mutual borders. This scheme is presented as one of the tools in the further more detailed study of the deep weakly explored part of the section. The complex consideration of the seismic, magnetic, and gravimetric measurements made it possible to substantiate one of the variants that justifies the geological nature and interpretation of the phenomenon areas associated with the Hobdin and Aralsor gravity peaks (Figure 2). For example, in the region of the Hobdin maximum, the value of the gravitational field is about 60 mGal, the magnetic field is characterized by the opposite behavior, which has a value of -20 nT and rises to +100 nT to the east of the maximum. A similar ratio of both fields indicates a high probability of the presence of carbonate rocks in the section. To this, according to the data of the KMPV (refraction correlation method), a sharp drop in the velocities above the level of the roof of the subsalt deposits is of the order of 3.4-5.4 km/sec. In accordance with these assumptions, in some parts of the central part of the Caspian the carbonate surface can lie at depths of the order of 4.0 km. Taking into account that the area of Hobdin and Aralsor maximum is about 22 thousand sq km and 6 sq km, respectively, further refinement and

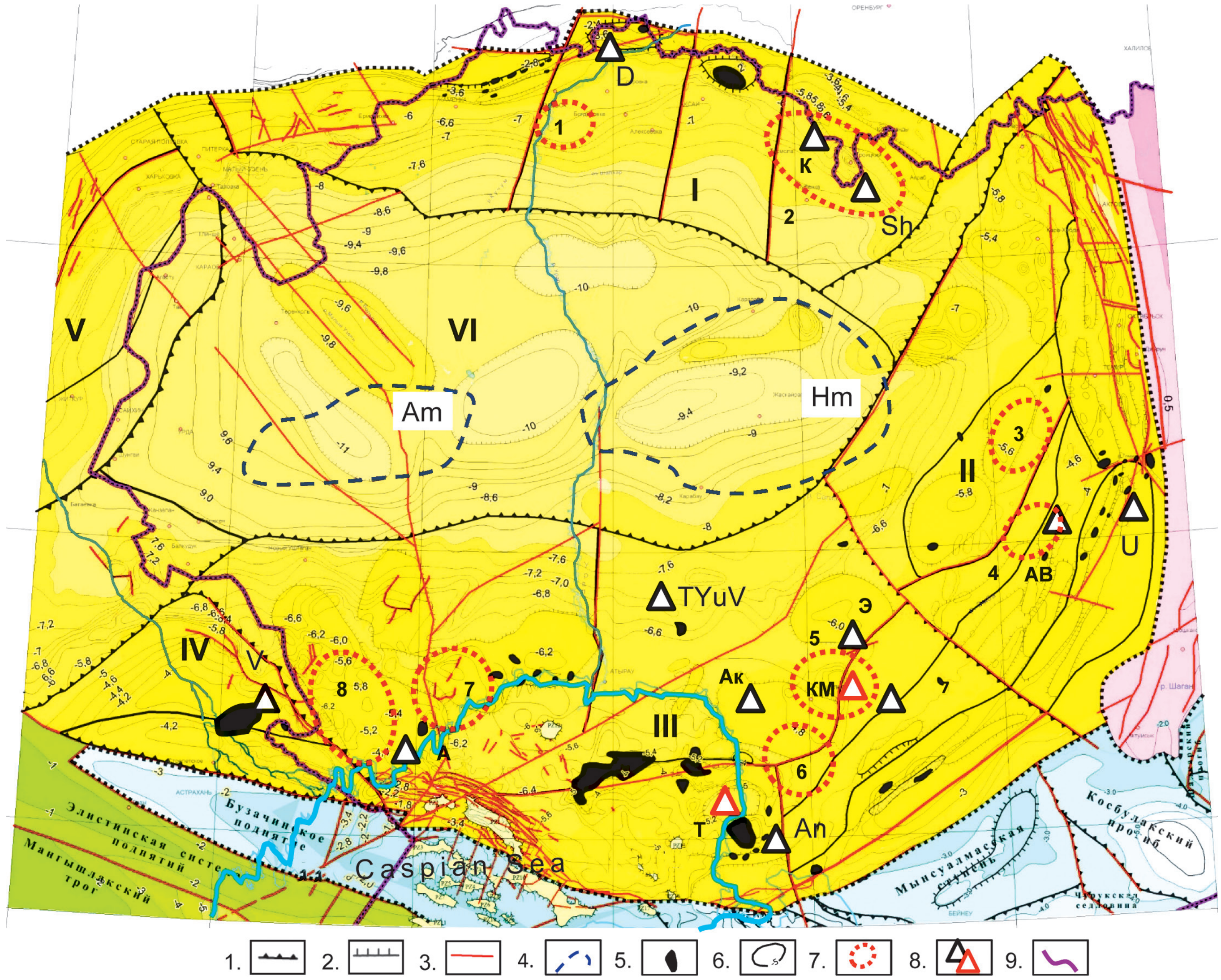

Figure 2. Scheme of the Paleozoic complex of the Caspian basin. Conventions: 1. Geoblocks: I – Northern, II – Eastern, III – Southern, IV – Astrakhan, V – North-West; 2. Contours of large structures of the upper order; 3. Regional faults; 4. Gravitational anomalies (maxima): Am – Aralsor, Hm – Hobdin; 5. HC fields; 6. Isohypes along the roof of Paleozoic deposits (OG P1), km; 7. Zones of development of large Paleozoic uplifts (protrusions of ancient formations): 1 – Zhelayevskaya, 2 – Koblandy-Shirak, 3 – Koskol-Shubarkuduk, 4 – Akzharskaya, 5 – Munayly-Adaiskaya, 6 – Kyzylkuduk-Matken, 7 – Zaburunye-Sazankurak-Oktyabrskoye, 8 – Alga-Kobyakovskaya; 8. Ultra-deep wells: a) the Paleozoic horizons that have opened at elevated depths (6.0 km and more): K – Koblandy K-3, D – Dolinskaya UGS-3, Sh – Shirak SR-1, AB – Akzhar Vostochny G-5, U – Urichtau U-5, B – Bikjal SG-2, E – Embinskaya P-1, Ak – Akatkol (Guryev arch) P-3, An – Ansagan G-2, TYuV – Tasim South-Eastern No. 1, A – Alga № 1, V – Volodarskaya №2; b) in drilling / in plan; 9. The border of the Caspian basin; 10. The border of neighboring states

detailing of their internal structure is one of the most urgent tasks.

In general, the results of the research on the CSSB RK Project provide analyzed and summarized data (text part, graphic and text applications) collected during the study period of 1990-2010 throughout the territory of Kazakhstan. All the data used in the process is digitized and presented in electronic form, convenient if necessary for operational and practical use in the analysis.

As a result of the strategy of searching for oil and gas fields at the turn of the 20th and 21st centuries, the central ones, the most submerged zones of the Caspian Basin, remain unexplored. The number of wells that have exceeded the depth mark of 6.0 km is currently limited, they are of the order of ten and are mostly drilled on the Paleozoic in the side zones (Figure 2).

Significant "headstart" for the subsequent detailed research has been carried out in the part of exploratory drilling in recent years. On the rise of Urikhtau on the eastern edge of the Caspian basin in 2014-2015 drilling of the well with a design depth of 6000 m was carried out (Azhgaliyev, 2015). However, due to the complication of the technical condition of the wellbore, a depression below the 5374 m mark was not possible. Despite this, according to the results of drilling on the area of Urikhtau, a fundamentally important result is obtained, confirming the productivity in the context of the Devonian deposits, the study of which, moreover, was the main purpose of the conduct of this well. In the south-east of the Caspian basin in the first half of 2017, the drilling of a super deep well 7.0 km deep on the Kyrykmergen-Munayly North uplift (the northern part of the Matken-Bikjalsky step) was started. A preliminary assessment and justification for the 8.0 km deep exploration well of Tengiz Glubokiy on the area of the same-named field was carried out in order to clarify the geological structure and the oil and gas content of the lower (middle – upper Devonian) level of productivity. Thus, the low values of the gravitational field in the Tengiz field, in contrast to all other major uplifts of the southern frame, allowed us to assume the oil contour mark below the presence of a strong decompaction zone and, correspondingly, their saturation of the hydrocarbon. In addition, the possibilities and preliminary data for the exploration well of a depth of 4.5 km on the Uzen-Karamandybas (Mangyshlak) ridge to study the structure and possible oil and gas potential of the promising Paleozoic strata were considered.

On the objects of research, based on the generalized and analyzed material, digital volumetric geological and basin models have been compiled, which in the future are expected to be transferred to the category of permanently operating basin models. The corresponding updated geological and geophysical data base was compiled on them. The work on the integrated study of basins was associated with a lack of full access to the accumulated geological and geophysical information, which represented an objective difficulty in achieving full-scale analysis and maximum coverage of the area for research.

At the same time, along with important results obtained, **a number of problematic issues of regional geology of sedimentary basins are identified**, which are of fundamental importance and require further solutions through a series of regional geological and geophysical studies that form the basis of the recommended and proposed Regional Research Program. The planning and staging of a large-scale regional study of the Caspian basin and the west of the Turan plate, along with the other sedimentary basins of the country, is based on the recommendations of the CSSB RK Project for 2009-2013. The basic stages of this program were previously detailed in the work (Akchulakov, 2015). With this in mind, the author in this article focuses on the basins of Western Kazakhstan with a broader argument regarding the need to drill abnormal depths (6.0 km and more). Thus, the ideological basis and focus of the **Program for the regional study of the basins of Western Kazakhstan for the period up to 2030** constitute the following principal provisions.

a) Until now, there is no well-founded, more accurate geodynamic model for the development of the entire territory of Kazakhstan and its constituent tectonic elements. Current models of development and structure are based on fragmentary and incomplete data, lower in terms of measurement technologies compared to those currently available to researchers.

b) The obtained results of magnetometric and gravimetric measurements indicate the presence of additional features in the behavior and tracing of the surface of the foundation, which makes it necessary to refine and determine the morphology and depth of the roofing of the foundation. We have to state that the data currently available do not allow us to solve these problems.

c) Almost in all the basins the main work in the study of shallow strata has been performed, mainly in the Meso-Cenozoic time complex. However, the present stage of geological exploration characterizes the transition to the study of the structure and oil and gas content of the intermediate complex of sediments and deep-lying sequences of Paleozoic age and older. Previously conducted studies at this time have solved this problem incompletely. Essentially, in the study of the deep structure of the basins, the work to solve this and other problems is at the initial regional stage.

d) The study of the oil and gas potential peculiarities of the basins made it possible to draw a definite conclusion about the deep source of hydrocarbon fluids for practically all basins. This determines, in turn, the need for systematic studies aimed at identifying the cause and effect relationships of oil and gas content of both the basins as a whole and their individual elements, with the features of geological development and the structure of deep horizons (up to the Moho surface). Because these aspects determine the tectonics and, accordingly, the deep processes controlling oil and gas accumulation and oil and gas generation.

The aim of the regional study program is to study the internal structure of sedimentary basins with the involvement of a complex of geological and geophysical methods. In this case, it is necessary to clarify the history of basin formation on the basis of data on the behavior of the main physical surfaces, starting from the Moho surface and above. It is necessary to study the material composition of the rocks composing the crystalline basement and the overlying deposits of the sedimentary cover, correcting the depths of the roofing of the foundation and the main seismic surfaces, clarifying the nature of the tectonic disturbances and the correlation of the main seismic surfaces with the aim of substantiating large tectonic sedimentation objects and zones within the basins.

The complex of regional methods includes carrying out magnetometric and gravimetric measurements of increased accuracy in the variant of area mapping at a scale of 1:50000, the analysis of space observations data, and the conduct of regional seismic studies in the Geotraverse variant, including the CDP method in the

DSS and RCM (deep seismic sounding and refraction correlation method) complex and the development of regional seismic 2D profiles (Figure 3). The Geotraverse profile system assumes measurements of magnetic, gravimetric, electric fields, and geochemical surveys.

For the purpose of studying the rock composition of previously undiscovered deep-lying complexes, the stratification of seismic reflecting horizons, the study of reservoir properties at great depths, and the geochemical features of individual sections, drilling of superdeep search (parametric) wells is planned. The scope and objectives of the regional basin study include the conduct of gravimetric, seismic (geotraverses and 2D area) works, aeromagnetic surveys and superdeep (exploratory, parametric) drilling.

Gravimetric studies. Within Kazakhstan so far, gravimetric studies have been carried out within the framework of the Federal Program for Geological Studies. At present, gravimetric works of scales of 1:1 000 000, 1:200 000, and 1:100 000 have been completed. Large-scale studies have been carried out on a scale of 1:50 000. It is necessary to supplement and complete the gravimetric studies of this scale. It is planned to carry out works within the Caspian and Ustyurt-Bozashi basins in the period up to 2025.

Aeromagnetic survey. Magnetometric studies covered almost the entire territory of Kazakhstan. Aeromagnetic studies, conducted in 2011-2012 in the Caspian Basin, showed significant differences with earlier studies. In this regard, it is necessary to continue similar studies on all sedimentary basins, including in the west of the Turan plate (Mangyshlak and Ustyurt-Bozashi). The volume of work is preliminary 140 thousand sq km. The survey, similar to the Caspian basin, is conducted over a network of 2 km x 10 km, with thickening of the network to 1.0 km x 10.0 km. The work is planned in the period until 2020 in stages.

Regional seismic studies include work on the study of deep-lying sequences of the Paleozoic complex within the prospective areas and suggest the development of regional (geotraverse) and regional (zonal) seismic profiles.

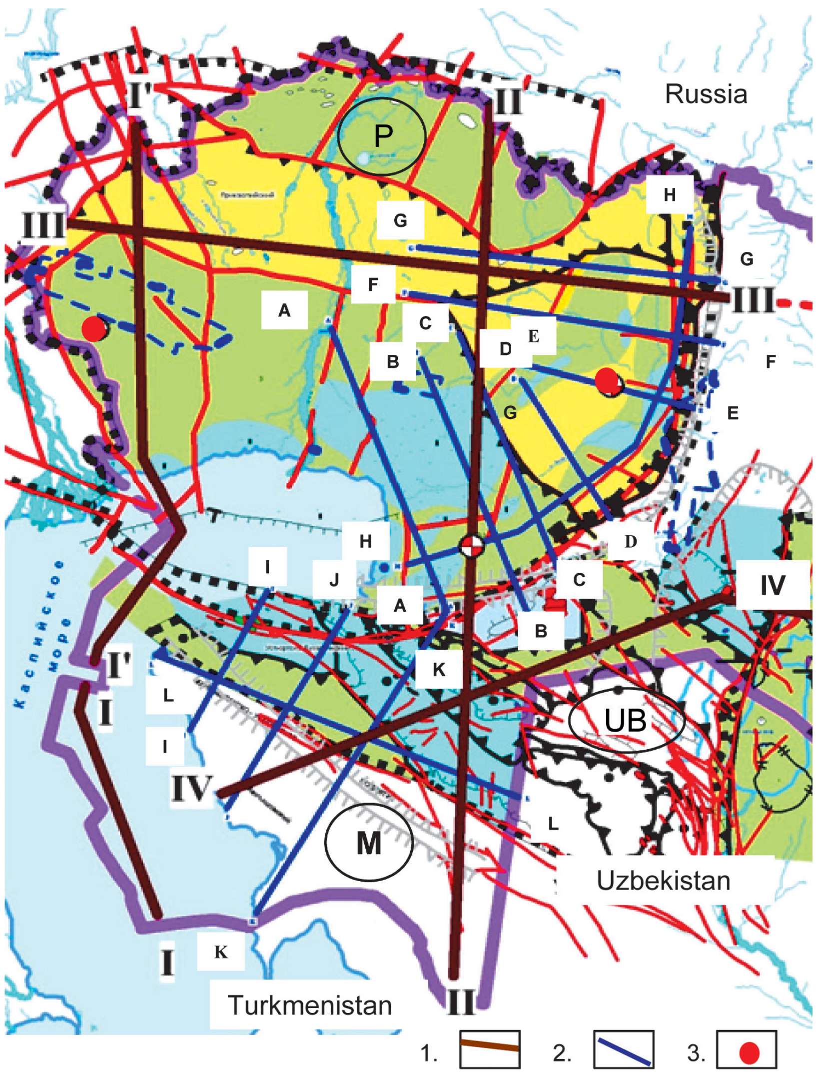

Figure 3. Western Kazakhstan (the Caspian basin and the west of the Turan plate). Scheme of geotraverse location and regional seismic 2D profiles. Conventions: 1. Geotraverse; 2. Regional 2D seismic profiles; 3. Preliminary position of design parametric wells; Basins: P – Caspian, UB – Ustyurt-Bozashi, M – Mangyshlak.

In total, according to the program of seismic surveys, it is necessary to conduct a minimum amount of research on the Geotraverse system, which is aimed at studying first-order facilities (oil and gas basins and areas) and their conjugation zones. In this case, the recording length is about 20 seconds.

The program of geotraverses includes the implementation of DSS-KMPV (on the basic profiles), high-precision profile gravity prospecting, magnetic prospecting, 2D-CDP method work with a recording length of up to 20 seconds, electrical exploration (MTS profiling, resistance method, VES) and geochemical surveys. Seismic work with geotraverses is planned in the future for all sedimentary basins and is calculated for the period up to 2025.

At the same time, the Caspian, Ustyurt-Bozashi, and Mangyshlak basins are the priority ones based on the results of the integrated assessment. Conducting regional works on the Geotraverse system in them is foreseen primarily; the **volumes are five geotraverses** with a total length of 2970 lin km (Table).

The system of regional 2D profiles is aimed at studying the structural features of large second-order zones within first-order objects with the purpose of studying their structure and detecting large local objects corresponding to the level of reservoirs with possible large and giant volumes of hydrocarbons (Figure 3). The volume of profiles is 4315 lin km.

No.	Geotraverse	Basin/Area	lin km	Term, years
1.	I-I	Mangyshlak, Ustyurt-Bozashi, the Caspian Basin	310	1
2.	I'-I'		730	2
3.	II-II		1100	3
4.	III-III		830	2
5.	IV-IV	Mangyshlak, Ustyurt-Bozash and Aral basins	900	2
	5 profiles in total, lin km		2970	

Basin, zone	2D profiles	lin km	Years
The Caspian basin (the south-eastern side zone)	A	390	2018-2019
	B	350	
	C	335	
	D	210	
	E	220	
	F	380	
	G	370	
	H	640	
Mangyshlak, Ustyurt-Bozashi, the Caspian basin (the southern flank zone)	I	200	2019-2020
	J	290	
	K	450	
	L	480	
Total volume of 12 profiles (lin km)		4315	

Table. The program of regional study of the basins of Western Kazakhstan (geotraverses and 2D profiles) for the period up to 2020

To date, geotraverse work has already begun and is being systematically carried out within the basins in the south-south-east of Kazakhstan.

The actual materials and available substantiating data make it possible to recommend and determine the drilling of superdeep (up to 8.0 km) prospecting wells at priority local Paleozoic structures (Azhgaliyev, 2015). The south-eastern, southern (interfluve of the Urals-Volga), the eastern, and northern instrument areas of the Caspian basin, as well as the Mangyshlak (Uzen block), are of primary importance in this regard. In the south-eastern frame, large uplifts are marked on the Matken-Biikjal and Namaztakyr stages, and the Kulsar zone of uplifts. In the interfluve of the Urals-Volga, promising areas of the Kum Severny-Kobyakovskaya-Alga and Zaburunye-Sazankurak-Oktyabrsky uplifts are highlighted (Figure 2). The lower Devonian-Lower Carboniferous floor in the Karaton-Tengiz zone of uplifts (the structure of Tengiz Glubokiy) is of great interest. In the north-north-east of the basin, the Koblunda-Tamdy, Chirac and Zhelayevsky uplift zones are of prime importance. In the east of the Caspian, large prospects for large objects in the Zhanazhol-Tortkolsky, Temir and Shubarkuduk-Koskol zones of valleys are grounded.

Ten drilling wells are top priority in the drilling program, in each of them, a full range of studies is mandatory, including an optimal list of GIS methods, core sampling, reservoir fluids and lateral soils. The period of work is until 2022.

The systematic implementation of the Program of regional study of sedimentary basins of Western Kazakhstan will undoubtedly accompany other important projects of global importance, including the Eurasia Project, which provides the drilling of an anomalous depth in the well (14-15 km) in the center of the Caspian (Kuandykov, Volozh, 2015). One of the main tasks in this case will be the optimal determination of the location of the superdeep "Prikaspiy" well. Together with this, the Program will provide new material and factual data on the deep structure and tectonics of the central areas of the Caspian Basin, which in turn will be additional material for assessing the structure and formation, especially in the Paleozoic and older stage of development, adjacent to the south basins Ustyurt-Bozashi and Mangyshlak.

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An integrated approach for produced water treatment and injection

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Abstract. During the process of the development and exploitation of oil reservoirs, a certain amount of reservoir water is produced along with hydrocarbon fluids. The volume of produced reservoir water does not remain constant over time. In the initial stages of production, relatively small amounts of water are obtained in the production. Due to a strong water drive and as time progresses the amount of produced water continuously increases. The final phase of production is often characterized by an enormous production of water, which significantly exceeds the quantity of produced oil. In highly waterflooded reservoirs, the quantity of produced water is over 90% of the total produced fluids. If well stimulations or waterflooding operations have been carried out, the properties and volume of produced water may vary even more significantly. The management of produced water is generally an expensive process, regardless of the oil price. There are usually large volumes of water to be treated, prepared and injected into the appropriate underground formations or aquifers. In this paper, the integrated approach for management of produced water will be presented, which will include constant monitoring of changes in the characteristics and volume of the produced water during the entire life cycle of the fields. Similarly, there will be a focus on the optimization of the water treatment and its disposal. Screening criteria will be presented according to the disposal formation quality and design of the water treatment system. Therefore, the decision tree will be designed according to the properties of the formation in which the treated water will be injected.

Keywords: produced water; water management; water treatment; produced water reinjection

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Introduction

Produced water is water from underground formations which is brought to surface during the oil and gas production. It is a source of many pollutants which can have negative effects on the environment. Produced water is the largest waste stream in oil and gas industry and its management presents a challenge requiring additional costs (Hagström et al., 2016). Water is present in every stage of the oilfield life cycle, from the exploration, through field development, production, and abandonment. The volume of produced water is not constant during a life cycle of the oilfield, because the water-oil ratio (WOR) increases during production (Khatib, Verbeek, 2003). The main causes of presence of produced water during the oil production are (Arnold, Burnett et al., 2004):

- Tubing, casing or packer leak,
- Channel flow behind casing,
- Raise of oil-water contact,
- High permeability layer without crossflow,
- Fractures or fissures between injectors and producers,
- Fractures or fissures from a water layer,
- Water coning or cusping,
- Poor areal sweep,
- Gravity-segregated layer,
- High permeability layer with crossflow.

Produced water is a toxic waste, and it must be properly treated and disposed according to environmental regulations. Produced water management options are (Evans, Robinson, 1999):

- Discharge to evaporation pond (deserts),
- Discharge to marine environment (offshore),
- Discharge to ground waters (onshore),
- Underground injection (underground layers, aquifers) (on/offshore).

Evaporation ponds can be used in places with high daily temperatures like deserts. For disposing into the sea or oceans, produced water must fulfill the environmental disposal standards (effluent concentration of oil in water ranges from 20-50 mg/l). Other solutions in onshore

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oilfields are injection into the underground formations or treatment of the produced water to the environmentally acceptable level, which in turn is very expensive (Evans, Robinson, 1999). Deep underground injection is safe because the treated water is far away from shallow aquifers that contain drinking and irrigation water. It is also expensive because it requires higher capacity with high injection pressures. Produced water requires appropriate technological, chemical and bacteriological processing before reinjection. It is necessary to remove all the components that adversely affect injection into underground layers. Produced water requires removal of dissolved and dispersed organic components as well as suspended solids and adjustment of the compatibility with underground waters, if needed. Since the produced water treatment and its disposal require substantial financial investment, the process of integration needs to be applied to minimize the costs of management.

The properties of produced water

Physical and chemical properties of the produced waters depend on many factors, including: geology, mineralogy, chemical reactions that have occurred during geological times, types of hydrocarbons, microorganisms, temperature and pressure (Veil et al., 2004). Produced water consists of suspended solids and different components soluble in water. These components are a mixture of organic and inorganic compounds with different levels of toxicity and biodegradability. Some of these components are naturally present in the produced water and some of them are added during the stimulations, or processing (Veil, Clark, 2011).

The major components of produced water are:

• Dissolved organic compound,
• Dispersed organic compounds,
• Dissolved minerals from formations,
• Chemicals,
• Solids (formation rock particles, corrosion, scale, bacteria, asphaltenes, waxes),
• Dissolved gases (Bretz et al., 1994).

The typical produced water properties are shown in the table 1.

The amount of oil that dissolves in the produced water depends on several factors: the types of hydrocarbons, the volume of produced water, artificial lift technique and production phases (Sunde et al., 1990). Dissolved organic components in the produced water are polar components and vary between low and medium range of carbon. Pressure, temperature and pH influence the dissolvability of organic components in produced water. The dissolved organic compounds include hydrocarbons (acyclic, cyclic and polycyclic hydrocarbons with two or three benzene rings), BTEX (benzene, toluene, ethyl benzene, and xylenes), poly aromatic hydrocarbons – PAH (with two or three benzene rings), nitrogen compounds (amino acids), fatty acids, naphthenic, and humic acid, and phenols (Daniel et al., 2005).

Produced water properties	Quantity
Concentration of oil in water	100-3000 mg/l
Total suspended solids	2-3000 mg/l
pH	5.1-7
Specific gravity at 15°C	1.03-1.15
H_2S	0-1000 mg/l
CO_2	50-2000 mg/l
Salinity	1-300 000 mg/l

Table 1. Typical produced water properties (Daniel, Bruce, Langhus, Patel, 2005)

Although produced water can dissolve many compounds, most of the oil compounds remain in the dispersed phase (Ekins et al., 2007). The dispersed organic compounds include polycyclic aromatic hydrocarbons (with more than three benzene rings) and heavy alkyl phenols. Dispersed oil is in the form of oil droplets dispersed in water phase (Stephenson, 1992). The concentration of polycyclic aromatic hydrocarbons and acrylic (alkylated) phenols are proportional to the dispersed oil content in the produced water (Faksness et al., 2004). Concentration of dispersed oil in produced water is very dangerous for the environment because the dispersed components have highly toxic and carcinogenic effects on living beings. Dispersed oil droplets cannot be effectively removed by the separation (oil/water separation) (Utvik, 1999).

The produced waters from oil and gas reservoirs are often characterized by increased mineralization. The dissolved minerals from the formation are high in concentrations and include cations, anions, heavy metals and radioactive metals (Faksness et al., 2004). Cations are Na^+, K^+, Ca^{2+}, Mg^{2+}, Ba^{2+}, Sr^{2+}, Fe^{2+} and the anions Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-. Cations and anions have a major impact on the chemical composition of the produced water, mostly on salinity and scale potential (Igunnu, Chen, 2014). The salinity of produced water varies from several mg/l to more than 300 000 mg/l. The greatest influence on salinity have Na^+ and Cl^- ions and less K^+, Ca^{2+}, Mg^{2+} (Jacobs et al., 1992). Heavy metals in produced water are present in traces and include chromium, lead, cadmium, mercury, silver, nickel, zinc and many others. Concentration of heavy metals in the produced water depends on the age of the wells and on the geological properties of the formation (Utvik, 1999). The common naturally occurring radioactive elements found in produced water is radium (^{226}Ra and ^{228}Ra), which is the main source of radioactivity, that could be indicated by barium ions.

The chemicals used during the production of oil and gas and during the produced water treatment include corrosion inhibitors, scale inhibitors, emulsion breakers, biocides, antifoam agents, coagulants, de emulsifiers, solvents, etc. (Stephenson, 1992). Chemicals may be in the form of pure components or in a solution (Hansen, Davies, 1994). The concentration of these chemicals in produced water varies from field to field, depending on the operations that were applied. The presence of these chemicals depends on their solubility in water, oil, or gas (Igunnu, Chen, 2014). When these chemicals get into the produced water they can adversely affect the separation of oil and water and increase its toxicity (Hansen, Davies, 1994).

Dissolved gases that can be present in the produced water are CO_2, H_2S and O_2. They may be present naturally or may originate due to bacterial activity or due to chemical reactions in the produced water (Igunnu, Chen, 2014). The amount of dissolved gases in the produced water depends on the pressure, temperature, degree of mineralization of water and gas composition. At lower pressures, the gas solubility decreases with increasing temperature. At higher pressures, the solubility of the gas decreases with increasing temperature, and with further increase of temperature, solubility increases (Kenneth, Stewart, 2008).

Most problems during the produced water treatment and re-injection caused by solid particles that can be found in oil and gas production, especially during production from unconsolidated formations like sands. Solid particles include small pieces of reservoir rocks, precipitates, paraffin's, scales, corrosion products, stimulation products (proppant), bacteria etc. (Hansen, Davies, 1994). Microbial activity in oil and gas reservoirs can cause corrosion of equipment, precipitation of iron sulphide and contamination of natural gas (Wang et al., 2012).

The presence of H_2S in the produced water based on chemicals, mostly from methanol which is used as a solvent. Bacteria may enter in the injection wells during the drilling and other operations on the wells as well as reinjection. If there is sufficient dissolved oxygen in the produced water, the activity of bacteria can be increased (Horacek, 1992). Reservoirs with waterflooding operations are good places for the development of colonies of sulphate / reducing bacteria that can produce H_2S (Rosnes et al., 1991).

Produced water treatment technologies

The reinjection of treated produced water is more frequently applied around the world, mainly because it is the only economic way to handle large volumes of water. Generally, with the injection of produced water in aquifer, it is possible to increase the oil recovery factor.

Produced water must be properly treated before injection in underground formations. The quality of treatment must fulfill injection criteria to prevent formation damage during water injection. The main treatment techniques include (Kenneth, Stewart, 2008):

- Gravity separation,
- Coalescence,
- Gas flotation,
- Cyclones separation,
- Filtration.

Gravity separators are usually the first devices in produced water treatment. The principle of gravity separation is described by Stokes law (Powers, 1990). The most common gravity separators are API separators and skim tanks.

The API separator is one of the most common gravity separation devices for isolating the free water from the waste stream. It can remove 60-90% of free water. During the separation process, most of the suspended particles will settle to the bottom of the separator, oil will rise to the surface and free water will be in the middle (American Petroleum Institute. Division of Refining, 1990). The performance of API separators depends on the design, retention time, inlet fluid properties, operating conditions and the effects of additives (flocculants or coagulants). They are ineffective when the oil droplets have diameters smaller than 150 microns and when they are in emulsion. As the oil droplet diameter decreases, retention time must be increased to get optimal results (Daniel et al., 2005).

Skim tanks are the simplest devices for produced water treatment, which operate on the principle of gravity separation and they are used as one of the primary devices for treatment. They are designed to enable large retention times of water, which results in a gravitational separation (Kenneth, 2007). Inlet concentration of oil in water can be between 500 and 100 000 mg/l and after treatment it decreases to 250 mg/l (Arnold, Burnett et al., 2004).

Coalescers operate on the principle of coalescence of small oil droplets in large droplets and then come to surface. They are fully closed, which eliminates the release of gases and vapors and the possibility of fire. The main types of coalescers are: parallel plate interceptors (PPI), corrugated plate interceptors (CPI) and cross-flow separators, which can be used for removal of suspended particles. In that case water flow between the plates is directed to opposite direction (upflow) that the suspended particles fall. It can be applied when the concentration of oil in water is up to 3000 mg/l. After coalescence, the concentration of oil in water is approximately 150 mg/l (Kenneth, 2007).

Gas flotation units operate on the principle of creating gas bubbles which adhere to oil droplets, and raise them to the surface where they are removed. The gases used in this process are air, nitrogen or other inert gases. The gas can be introduced into the flotation cells in two ways: using pressure or induced. Gas flotation requires additives, coagulants, polyelectrolytes and de-emulsifiers which affect the flotation efficiency (Arnold, Burnett et al., 2004). Gas flotation should be used when the concentration of oil in water ranges between 250-500 mg/l. Solid particles can also be removed by gas flotation by gas bubble attachment to solid particles, reducing their weight and raising them to the surface where they are removed.

Cyclones are devices operating on the principle of gravity separation and can separate liquids form liquids, and solid particles from liquids, on different densities basis. Depending on the design, cyclones can remove particles with diameters of 5-15 microns and suspended oil droplets with diameters up to 30 microns (Arnold, Burnett et al., 2004). Cyclones require a pumping capability of about 5 horsepower that will create sufficient pressure to operate the hydro cyclone (Bennett, 1988). With no moving parts, maintenance is not expensive.

There are two main types of hydro cyclones which are used in produced water treatment, de-oilers – to remove oil from water and de-sanders – to remove suspended solids from water. De-oilers use the centrifugal force to separate the oil from the water. Hydro cyclone rotation creates a vortex, which directs oil drops towards the vortex where they are removed (Szép, Kohlheb, 2010). Total retention time of fluid in a hydro cyclone is about 2-3 seconds. De-sanders are used in the removal of solids from liquids, which makes them very useful devices in the initial stages of elimination of particles (Bennett, 1988).

Filtration can remove the dispersed oil droplets as well as solid particles. Filter media can be: walnut shell, sand, fibers, and others. Filtration cannot remove dissolved salts and thus the effect of filtering does not affect the concentration of dissolved salts (Veil, Clarck, 2011). Sand filters are mostly used to remove metals from produced water but this requires series of pre-treatment such as pH adjustment, de-aeration and solid removal. To remove solid particles by filtration, filters with fixed or non-fixed pore structure must be used. Pressure variations in the filter can cause minor deformations or displacement of the filter media and thus potentially change the size of some pores in the medium (Bennett, 1988).

Produced water reinjection

Treatment of produced water takes special place, not only by ecological reason, but also because of being a major component of the cost of producing oil and gas. The best solution is injection of treated water in waterflooded wells, because it does not require drilling and completion which reflects on total expenses. Waterflooding has been used to maintain pressure and to improve the recovery factor of the reservoir as well as to dispose of the produced water for environmental reasons. In most cases, produced water is injected at a pressure under the fracture gradient to maintain good performance with the formation. Mechanical formation damage issues associated with fines migration may also be problematic.

The quality of the produced water is an important factor which has a high influence on this process. Produced water should not contain oxygen to avoid corrosion in the injection equipment. Solid particles can clog the pore channels and impair injectivity. Those factors can cause the damage that can limit the injection, which in turn increases the costs of injection processes (Abou-Sayed, 2005).

If the aquifers are too deep and require expensive equipment for pumping, treated produced water can be injected in shallow underground layers. It requires drilling new wells and their completion, which reflects on the total costs, and there is a possibility for pollution of fresh water sources, which is environmentally unacceptable. The large increase in pressure at the start of injection process indicates a clogging with solid particles and forming a filter cake in the near wellbore zone. Well injectivity can be improved by matrix acidizing or fracturing.

It should be mentioned, that produced water is usually treated with various types of chemicals. The precipitation of calcium carbonate is one of the biggest problems in water treatment systems, especially in high temperature and high-pressure environments where the solubility of calcium carbonate decreases with increasing temperature (Yi, Jiang, 2008). Chemicals contain carbon, nitrogen and phosphorus and can serve as substrates and/or nutrients for bacteria. As a result, the bacteria colony cans rapidly increase and cause corrosion effects. Bacteria can grow in groups and colonies, attached to the solid phase or suspended in water. Bacterial activity can cause corrosion and pore clogging. Biocides are using as additives in controlling bacteria growth (Sunde et al., 1990).

The concept of integration applied in produced water management

The main priority during the treatment of produced water should be monitoring of any changes in the properties of produced water, especially when the volume is changed. The complexity of the treatment plays a significant role in the produced water management because any significant change of the water properties must be reflected in the treatment.

The concept of integration in produced water management is based on integration of four main factors and shown in the Figure 1:

- Data,
- Tools,
- People,

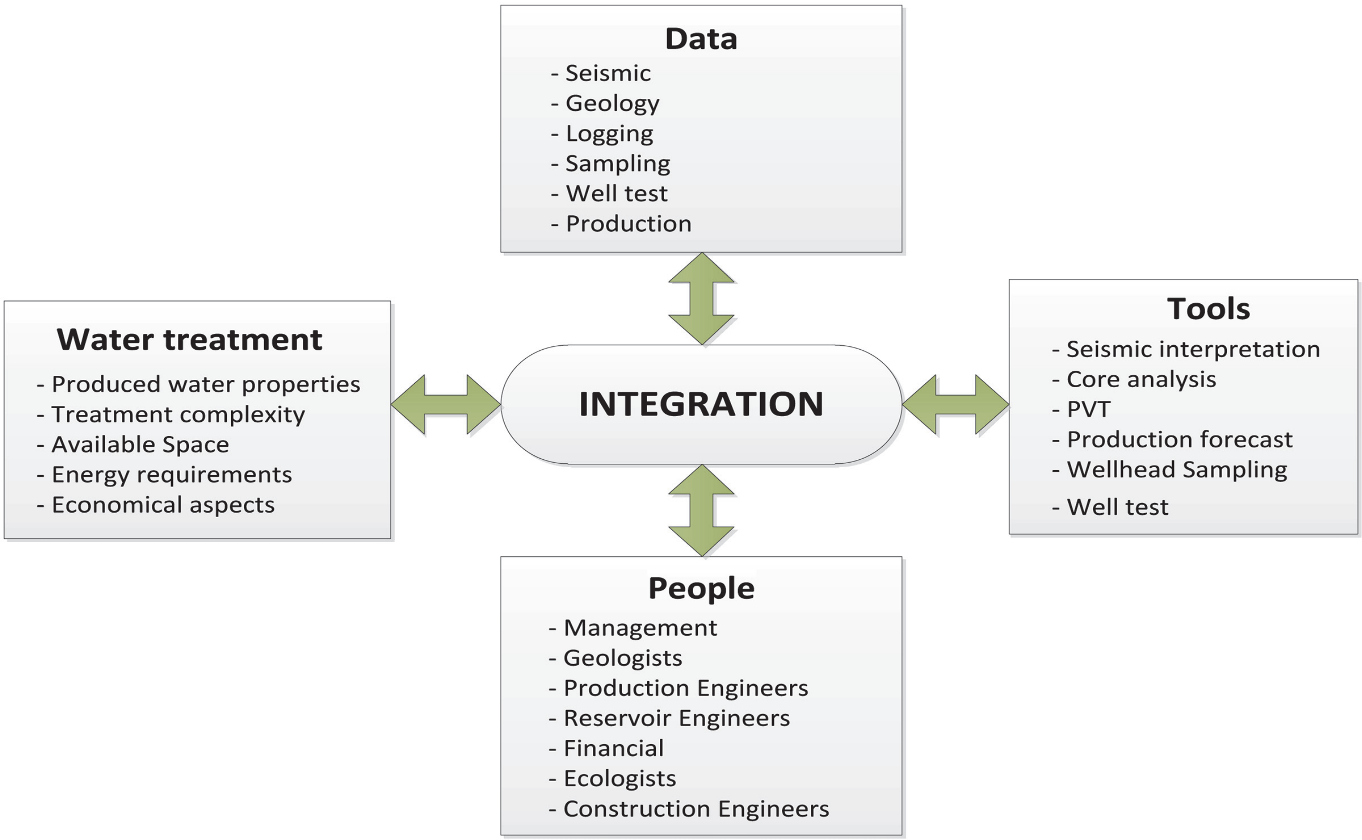

Figure 1. Integrated produced water management

• Water treatment.

Interpretation of high resolution seismic data, the presence of water zones and aquifers can be detected in the early stages of reservoir discovery. Geological data like lithology, mineralogy and depositional environment are useful in the characterization of produced water. Aquifer thickness, porosity and permeability of the aquifer, water saturation, gas-water or oil-water contacts are all useful data obtained from well logging techniques. From sample analysis, the most important parameters are chemical composition, the amount of dissolved and dispersed organic components, salinity, scaling tendency, corrosivity, the presence and the origin of suspended solids, the amount of dissolved gas in water, the density and viscosity of the produced water and its compressibility. From the well test interpretation, the most important data is the quantity of water that can be obtained in the production at various flow rates of oil or gas. During production, the quantity of water is constantly monitored by closely watching the changes in produced volumes.

The main tools used in the analysis of produced water include: seismic surveys; core sampling; PVT analysis; production analysis and forecast; surface sampling; well testing and reservoir simulation.

One of the most important aspects of the integrated produced water management is cooperation of various personnel involved in oil production. The board of directors must organize and raise cooperation between engineers of different profiles to exchange data and improve the common database. The team who needs to be involved in the produced water management should have petroleum engineers, reservoir engineers, geologists, production engineers, financial engineers, ecologists and civil engineers.

The availability of space on the field is a very important parameter and can have a significant impact on the treatment especially when choosing horizontal or vertical separating structures. The availability of energy is another factor to be taken in consideration when planning water treatments due to the amounts of energy used to complete the produced water treatments. Economic aspects must be justified by optimizing treatments to ensure that we have the lowest cost for the most optimal treatments.

The concept of integration in produced water management takes into account not only mentioned above aspects, but also less meaningful factors, such as: mixing of produced water, compatibility of water or type of underground formations.

Mixing produced water with different properties from various sources is not recommended, as it can lead to precipitations and deposition of different types of scales, such as: calcium carbonate, calcium sulphate, barium sulfate and strontium sulfate. Scales are formed in the tubing, pipes and the water treatment equipment, as result of changes in temperature and in pressure during the treatment. Damages in surface production facilities caused by scale precipitation could be very severe, causing reduction in diameter as well as clogging of pipes and other flowing surfaces. If the waters are incompatible, scale inhibitors must be added to prevent scale precipitation.

Compatibility of water can be determined experimentally or computationally. Several testing protocols exist for evaluating compatibility of water and scale tendency. The most common scales that are formed during the water treatment are Calcium Carbonate ($CaCO_3$), Calcium Sulfate ($CaSO_4$), Barium Sulfate ($BaSO_4$) and Strontium Sulphate ($SrSO_4$).

Type of underground formation for produced water injection. This factor presents the basis for the design of produced water treatments in this study. The types of formations for water injection considered in this study are:

- Naturally fractured formations characterized with large number of fractures and allow the injection of produced water with less quality;
- Highly permeable formations, characterized by high values of porosity (>25%) and permeability (>300 mD) as well as a high capacity storage of produced water;
- Medium permeable formations, characterized by medium values of porosity (12-25%) and permeability (100-300 mD);
- Low permeable formations, characterized by low values of porosity (<12%) and permeability (<100 mD).

In this section the produced water treatment screening process based on a formation quality is performed (Figure 2).

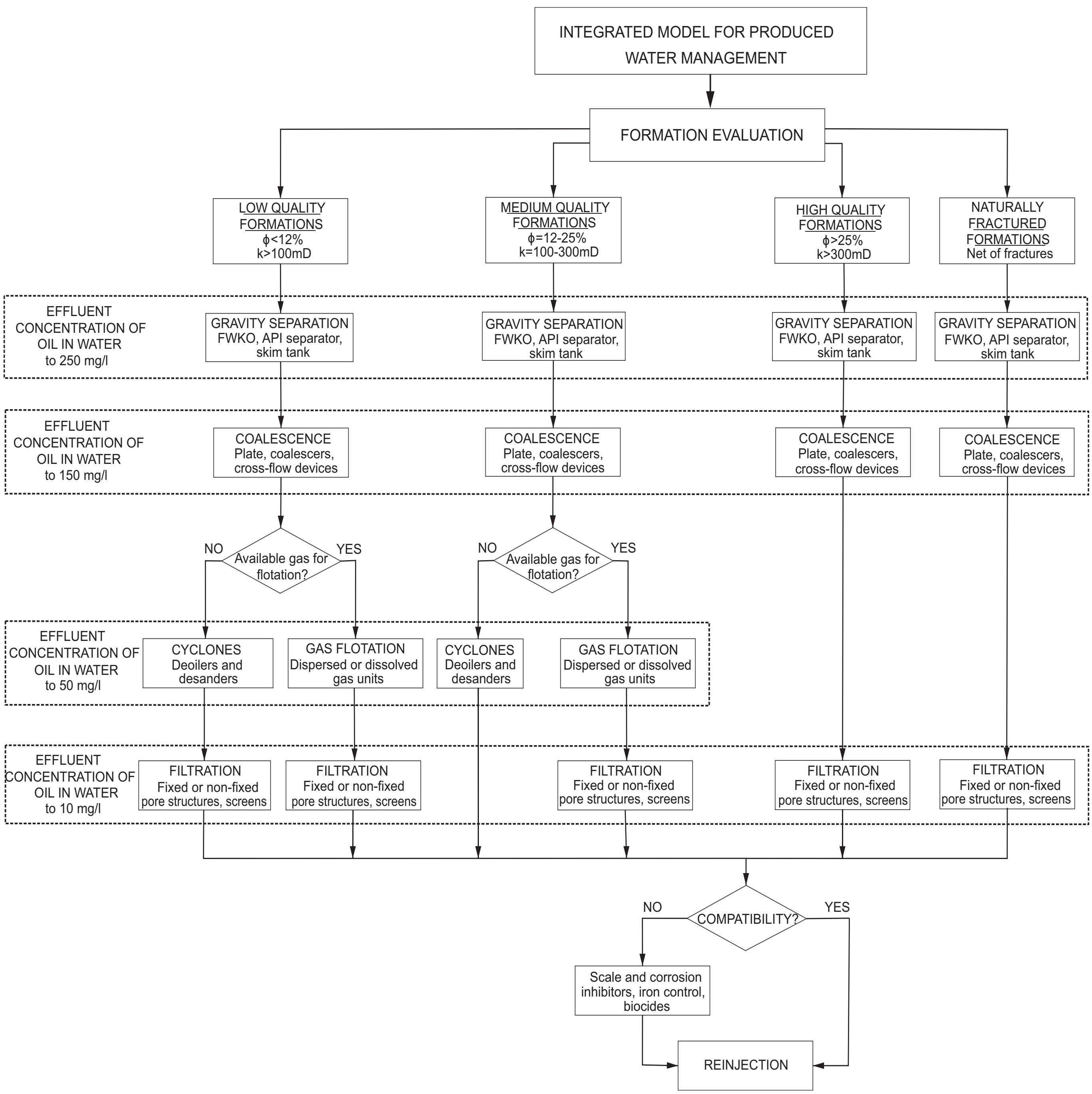

Figure 2. Flow charts for produced water treatment screening process based on a formation quality

Conclusions

Produced water management has become a major effort in the oil and gas industry. Environmental regulations about produced water treatment and disposal require more water reinjection into underground layers and aquifers. Produced water is an integral part of the production system and requires proper management to satisfy environmental regulation. The biggest problem is the injectivity decline during the reinjection processes. The main challenge is to ensure the long-term injectivity by preventing the formation impairment. This paper reviews the produced water properties, produced water treatment technologies and formations, in which the water is to be disposed. Screening criteria which suggests the proper produced water treatment process based on the quality of a different disposal formation are presented in this paper. The proposed model adapts the properties of formation to water treatment using the conventional equipment.

Proposed guidelines for water treatment are:

• Monitor the effluent oil droplets diameter; diameter must be less than the mean diameter of pore channel;

• Monitor the concentration, shape and origin of suspended solids and optimize proper filter system according to the diameter of pore channel;

• Minimize the water treatment cost by using conventional water treatment equipment;

• Monitor the scaling and corrosivity tendency;

• Monitor the compatibility of treated water with reservoir water;

• Enhance the cooperation between production and reservoir engineering departments in order to forecast produced quantities of water and plan operations accordingly.

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ASP project. Problematics of dissolved oxygen. Theory and practice

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Abstract. The article presents the latest results of studies of dissolved oxygen affect on efficiency of ASP flooding project being executed by Salym Petroleum Development N.V. Company. Pilot project associated with experimental injection of solutions of anionic surface-active substance (surfactant), soda and polymer into formation for enhanced oil recovery (ASP project) has been implemented since 2016. Stability of one of ASP components – polymer strongly depends upon presence of iron, hardness cations and dissolved oxygen in water. As long as polymer is used for injection on two project stages, which are the main and the most extended, at the stage of ASP unit design a complex of polymer protection from negative factors was considered, particularly impact of oxygen, which causes not only oxygen corrosion, but also irreversible destruction of polymer chains. The article describes studies of polymer solution stability, contains analysis of viscosity loss in the course of time in presence of iron and oxygen for polymer solutions. It justifies selection of chemical deoxygenation method for dissolved oxygen control. The article describes program of ASP laboratory studies and analytical instrumentation applied. It provides ASP process scheme and recommendations for technology implementation.

Keywords: ASP flooding, EOR, ASP Pilot project, West Salym oil field, dissolved oxygen, free-radical degradation mechanism, chemical oxygen scavenging, nitrogen blanketing, amperometrical method, polymer stability

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Introduction

Salym Petroleum Development N.V. is executing Pilot project for experimental injection of solutions of anionic surface-active substance (surfactant), soda and polymer into formation for enhanced oil recovery. Active injection of ASP solution (anionic surfactant, soda, polymer) started in July 2016, the next phase – polymer flooding – was implemented in 2017. The project will be completed by the end of Q1, 2018. Stability of one of ASP components, polymer, strongly depends upon presence of iron, hardness cations and dissolved oxygen in water. In order to remove potential negative effect of dissolved oxygen ASP project includes a number of actions focused both on removal of dissolved oxygen from water and restriction of its ingress from atmosphere or chemicals in the process of operation. Detailed description of ASP project and aspects of oxygen management: from determination of its negative effects to methods of its removal and control over its concentration for future ASP projects are reviewed in the paper (Erke, Kostina, Bondar et al., 2018).

This article presents the latest results of studies of dissolved oxygen effect on efficiency of ASP flooding.

Effect of dissolved oxygen in ASP project

Polymer applied in ASP project is partially hydrolyzed polyacrylamide – in conditions of chemical flooding it is exposed to be impacted by high temperature, pressure, shear stress, hardness salts dissolved in water, iron and dissolved oxygen, which affects its stability (Erke, Kostina, Bondar et al., 2018).

As long as polymer is used for injection on two stages of the project (at first injection of ASP solutions and then injection of polymer solution), which are the main and the most extended, on the stage of ASP unit design we developed a complex of polymer protection from the above-mentioned negative factors, especially from oxygen impact, which causes not only oxygen corrosion but also irreversible destruction of polymer chains (Isabel Vega et al., 2015; Seright, Skjevrak, 2014; Wellington, 1983), also due to free radical mechanism, which results in irreversible loss of solution viscosity meaning loss of its target properties (Erke, Kostina, Bondar et al., 2018).

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Partially, such chemical sensitivity of polymer is used when polyacrylamides are applied for treatment of wells, when solutions of strong oxidizers – peroxides (so-called polymer breaker) being sources of radicals (due to unstable -O-O- connection) are used for their destruction.

Mechanism of degradation (loss of target viscosity properties) under impact of oxygen can be described with the following reactions:

$$R-H+O_2 \leftrightarrow R\cdot + HOO\cdot$$

$$R-R+O_2 \leftrightarrow R\cdot + ROO\cdot,$$

where R-R – Section of polymer chain. When started, the reaction occurs by chain mechanism:

$$ROO\cdot + R-H \leftrightarrow ROOH + R\cdot.$$

In the presence of active ions or molecules, for example, strong oxidizers or reducers, or ions of transition metals, such as iron, generation of free radicals becomes stronger, which accelerates the process of polymer chain destruction.

The Company performed own studies of stability of polymer solutions, one of results is provided in Figure 1, which is aligned with general principles (Seright, Skjevrak, 2014,).

Presence of iron ions accelerates the process of free radicals release with involvement of oxygen (Isabel Vega et al., 2015; Wellington, 1983), but in deoxygenated medium the impact of iron is insignificant, which is also described in (Isabel Vega et al., 2015; Wellington, 1983) and in our stability tests.

In presence of iron (or cation of other transition metal or oxidizer) and oxygen, mechanism of free radicals release occurs according to the following reactions:

$$Fe^{2+}+O_2 \rightarrow Fe^{3+}+O_2^{-}\cdot$$

$$Fe^{2+}+ROOH \leftrightarrow RO\cdot + OH^{-}+Fe^{3+}$$

$$Fe^{3+}+ROOH \leftrightarrow ROO\cdot + H^{+}+Fe^{2+}$$

$$ROO\cdot + R-R \leftrightarrow ROOR + R\cdot,$$

where R-R – Section of polymer chain.

In the above reactions it is important that simultaneous presence of iron and oxygen in water causes the biggest impact on length of polymer chain, and therefore on polymer viscosity. The other side of presence of trivalent metal ions is cohesion of polymer chains between each other, which will abruptly increase solution viscosity above the required value. This issue was raised in (Seright, Skjevrak, 2014), however in ASP project there were no preconditions for iron level increase, even taking into account corrosion of extensive sections of pipelines, to the level when cohesion of polymer chains in solution starts; iron was present in water in amounts directly activating chain radical mechanisms.

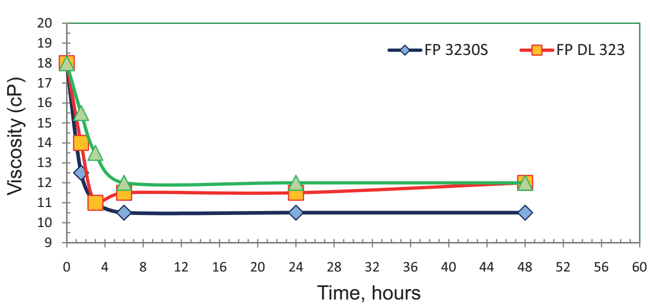


Figure 1. Diagram of viscosity loss in the course of time in presence of iron and oxygen for polymer solutions of Flopaam series (FP 3230S – applied in the project) in solution with polymer concentration of 2500 mg/l, iron – 5 mg/l, oxygen 10 mg/l, at temperature 83 °C

As long as pipeline electrochemical corrosion (and therefore presence of ions of iron and other heavy metals in water) cannot be fully excluded, even after water treatment including desalting on reverse osmosis membranes, it was decided to focus all efforts on removal of dissolved oxygen (deoxygenation) with process mode norm of not more than 10 mkg/l and protection of the process from atmospheric oxygen (Erke, Kostina, Bondar et al., 2018) and oxygen coming into the system along with ASP components.

Mechanism of viscosity reduction partially has free radical nature, and that means that reaction can progress not only by oxidizing principle – with involvement of oxidizers, but also with involvement of reducers, which also should be taken into account.

Oxygen management methods applied in Pilot project

Review of dissolved oxygen management methods and their application in ASP flooding pilot project are described in the paper (Erke, Kostina, Bondar et al., 2018). The project is being executed at several infrastructure facilities; the main facility of the project process scheme is unit for treatment and injection of ASP chemical solutions. The main sources of oxygen ingress into the process in this process scheme are: artesian wells, bulk chemicals granules of which contain voids with atmospheric air, surface active substances (surfactants) and isobutyl alcohol (IBA). Atmospheric oxygen can dissolve in case of contact with water in vessels and tanks (balanced concentration of oxygen in real conditions may reach 9-10 mg/l). Therefore oxygen management is simultaneously performed in several areas (Erke, Kostina, Bondar et al., 2018):

- Creation of nitrogen blanketing in all vessels and tanks in order to exclude contact of fluids with atmospheric oxygen. Nitrogen is generated in nitrogen-air station;
- Chemical scavenging of dissolved oxygen by dosing reducer immediately after water treatment taking into account oxygen excess coming in downstream of dosing point (with chemicals, etc.);
- Control over water-chemical mode of chemical scavenging of oxygen (pH, alkalinity, temperature, etc.);

• Continuous analytical control over oxygen concentration in various process streams for timely identification of oxygen ingress sources and its removal, control is performed both with use of instrumentation and by various laboratory methods.

Selection of dissolved oxygen management methods

Two methods of oxygen management were initially reviewed during development of ASP project:

• Membrane deoxygenation on membrane contactors (Klaassen, Feron, Jansen, 2005) operating in nitrogen-vacuum scheme, because nitrogen station is applied in the project regardless of selected oxygen management method and is able generate nitrogen of required quality – not lower than 99.8%; principle of operation and appearance are shown in Figure 2.

• Chemical deoxygenation (scavenging of dissolved oxygen with reducer).

Traditional deaerators widely applied in energy industry were not reviewed due to equipment size and cost.

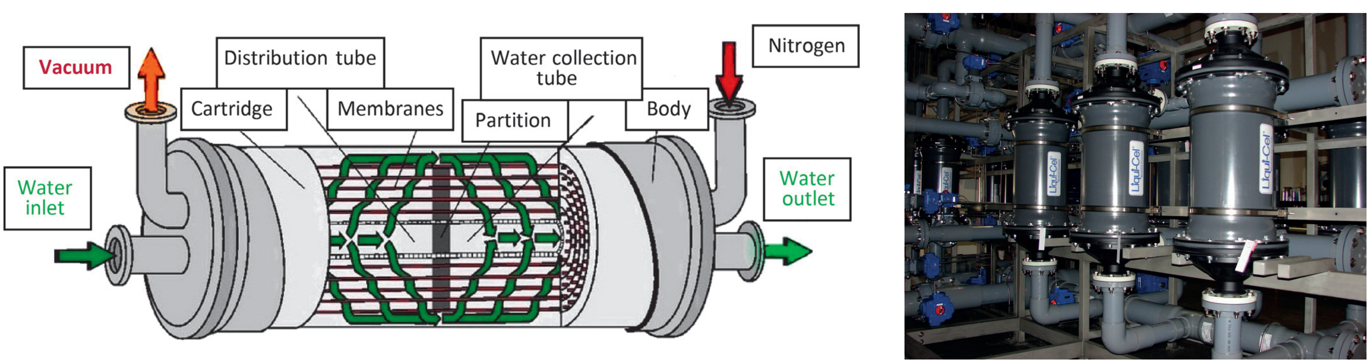
Economic calculation by total costs for project life cycle (about 1-1.5 years) showed efficiency of the second option, in addition contactors would have complicated already complex process scheme of water treatment (Erke, Kostina, Bondar et al., 2018). But for future projects this method can be applied, if, for example, dissolved oxygen and dissolved carbon dioxide should be removed simultaneously.

For implementation of the second method screening of different oxygen reducers-scavengers based on organic and inorganic sulfite-containing substances are performed, including laboratory testing of selected chemical (Table 1).

Despite a number of obvious disadvantages, such as generation of sulfates in the process of reaction with oxygen, limited operating range of pH and temperature, sulfite-containing (sulfites, bisulfites, metabisulfites) scavengers were selected for further processing mainly because they are cheap and easily accessible, and also due to easy involvement into operating process as well as due to operation mode of dosing equipment. In addition, sulfites can generate protective film (as stated by the manufacturer) on equipment walls, which contributes into reduction of oxygen corrosion rate (Erke, Kostina, Bondar et al., 2018). Herein sulfites mean sodium bisulfite, sodium sulfite and sodium metabisulfite, including with catalyst.

During laboratory testing a process of oxygen scavenging with AMINAT™ KO-2 (The chemical safety passport AMINAT™ KO-2 according to TS 2149-098-17965 829-03 of the company CJSC "ECOS-1") chemical was simulated and impact of various factors on kinetics of reaction (pH, impact time, temperature, etc.) was estimated. Description and results of experiments for assessment of AMINAT™ KO-2 efficiency during deoxygenation of distilled water are provided in (Erke, Kostina, Bondar et al., 2018).

Basing on results, in order to provide conditions for chemical deoxygenation process in distilled water it is required to additionally perform dosing of alkaline chemicals. Experience in deoxygenation of distilled water with alkalization to pH = 6.7 showed high



A B

Figure 2. Principle of operation (A) and appearance (B) of membrane contactors for deoxygenation

Oxygen scavenger	**Passivating properties**	**Increase of salt concentration**	**Toxicity**	**Stoichiometric consumption for 1 mg of O_2**	**Commodity form**
Sodium sulfites	no	yes	No data	7.9	Powder, solution
Hydrazine	yes	no	Toxic, carcinogenic	1.0	Liquid
Carbohydrazine	yes	no	No data	1.4	Liquid
Methyl-ethyl-ketoxime	yes	no	No data	5.4	Liquid
Hydroquinone	yes	no	No data	6.9	Liquid
Di-ethyl-hydroxylamine	yes	no	Safe	1.2	Liquid

Table 1. Chemicals review– oxygen scavengers ((Erke, Kostina, Bondar et al., 2018) with supplements)

efficiency of chemical even at low temperature. Almost full oxygen scavenging occurred even during the first minutes of the experiment, and after ten minutes oxygen concentration decreased to required values of 10-15 mkg/ dm^3 (Erke, Kostina, Bondar et al., 2018).

Basing on performed studies for assessment of reverse osmosis permeate chemical deoxygenation with use of AMINAT™ KO-2 chemical efficiency it is possible to make the following conclusions (Erke, Kostina, Bondar et al., 2018):

1) Efficient chemical scavenging of oxygen in the process of AMINAT™ KO-2 dosing occurs in case of long alkalization, thus providing pH value of treated water above 6.2-6.3;

2) Duration of permeate residence in accumulating tank after dosing of AMINAT™ KO-2 chemical does not affect the efficiency of deoxygenation during further water heating;

3) Recommend to perform permeate alkalization upstream and downstream of accumulating tank with correction of dosing by pH value, use more alkalized forms of chemicals, for example, sodium sulfites or sodium bisulfites.

Also, it should be noted that there is an alternative to the above-mentioned methods to remove negative impact of oxygen – use of polymers with protective additives such as urea and thiurea. Molecules of urea interact with radicals and connect into stable molecules:

$$R \cdot + (NH_2)_2CS \leftrightarrow 2(NH_2)_2CS \cdot + R;$$

$$2(NH_2)_2CS \cdot \rightarrow (NH_2)_2CS - SC(NH_2)_2.$$

Such or similar additives are often used by manufacturers of polymers when it is required to compensate negative interaction, including oxygen, hydrogen sulfide, etc. For the Pilot project it was decided to take the selected way (chemical scavenging of oxygen) due to high price for special protected polymers.

Dissolved oxygen management during operation. Water-chemical mode

In process of operation pH change in clean water tank was identified where reverse osmosis permeate is supplied (having reduced pH value due to carbonic acid). The pH factor was decreased below 5.0 units due to hydrolysis of metabisulfite, which reduced chemical efficiency. By results of studies it was decided to increase pH value only in clean water tank by dosing soda ash solution (Erke, Kostina, Bondar et al., 2018).

The dynamics of oxygen concentration in various streams was also analyzed. In case of shutdown of nitrogen blanketing of volumetric equipment or contact with atmosphere (for example, in process of pre-commissioning operations or shutdowns) abrupt increase of oxygen concentration was observed, which was the result of water system tendency to come to balanced concentration of dissolved oxygen in specific conditions (Rubin Battino et al., 1983; Kai Fischer, Michael Wilken, 2001) (Figure 3).

In process of pre-commissioning and startup of ASP project when injection of surfactant solution, its co-solvent, isobutyl alcohol (IBA), soda, salt and polymer into the reservoir was started, in final mixed

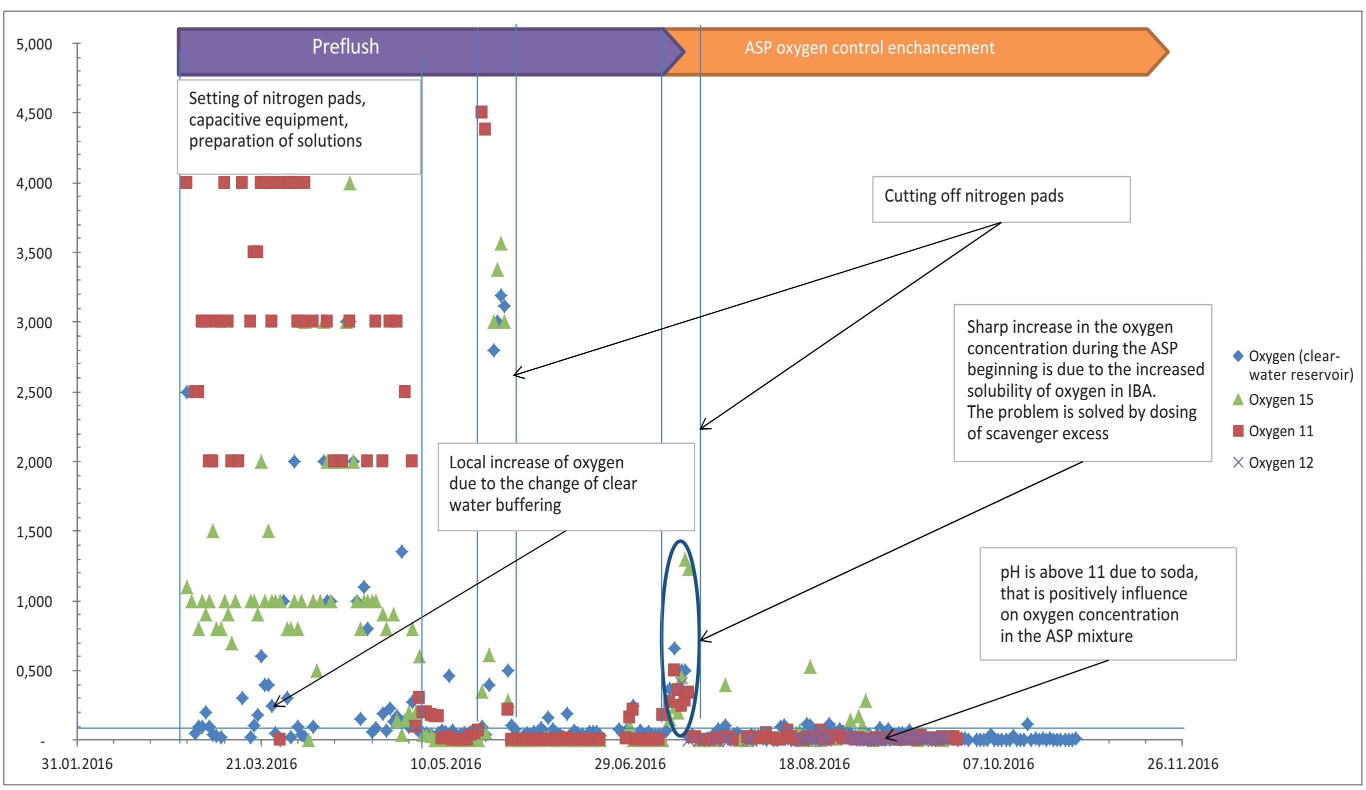


Figure 3. Dynamics of oxygen concentration in various flows during the implementation of the ASP Pilot project (Erke, Kostina, Bondar et al., 2018)

solution abrupt increase of oxygen concentration was observed. It was defined that jumps in oxygen concentration change recorded with inline analyzer were aligned with readings from sensors of IBA instant flow rate. It is associated with high oxygen solubility in alcohols, including isobutyl alcohol. Thus, IBA filling in truck tanks occurs not in fully sealed and isolated conditions, oxygen dissolved in IBA was coming into ASP solution and the sensor was recording that (Erke, Kostina, Bondar et al., 2018). It is noted that balanced concentration of oxygen in alcohol may reach dozens of mg/l (Kai Fischer, Michael Wilken, 2001; W. Rodgers Baird, Robert T. Foley, 1972). Attempts to perform measurement of oxygen content resulted in wide range, from several mg/l to 50-80 mg/l.

In order to guarantee removal of oxygen coming from IBA or other source it was decided to increase excess of sulfites with further reduction to 10-15 mg/l, as a result of which oxygen concentration reduced within several days. Then it was decided to reduce excess of sulfites and increase it only in cases of unexpected deviations from process mode norms (shutdown or insufficiency of nitrogen blanketing, loss of containment of tank equipment, etc.).

Recommendations on use of sulfites were also developed, because their use can have a number of side negative effects in West Salym as well as on other fields: sulfates as products of oxygen scavenging are processed by sulfate-reducing bacteria (SRB) producing hydrogen sulfate which leads to active corrosion of equipment and pipelines. Also barium in formation waters will produce barite (form of barium sulfate), sediments of which are extremely difficult to remove even with strong acids.

Sulfites as strong reducers, can also participate in radical reactions of polymer degradation, which means necessity of control over concentration of residual sulfites in water, but most sulfites after reaction with oxygen produce sulfates, anions inert in relation to free radical mechanisms, and residual sulfites in produced concentrations do not significantly affect viscosity. This was taken into account during development of program for control of water-chemical mode.

Analytical control program

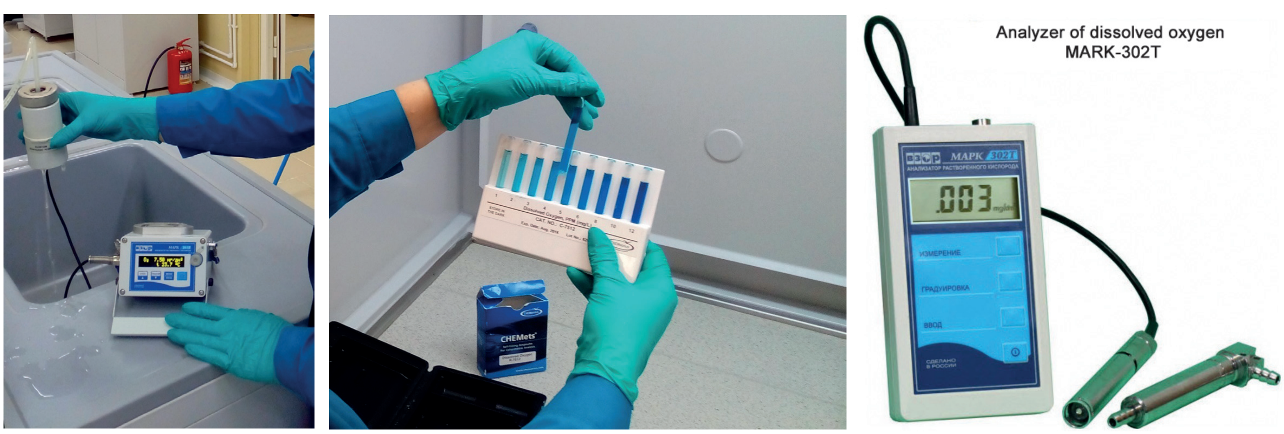
Program of laboratory studies of ASP projects contains over 38 analytical indicators and over 45 applied methods, both standard (regulatory documentation, RD, GOSTs, ASTM) and specially developed for the project. Frequently several methods were simultaneously applied for key indicators, which is associated with the fact that the same indicators in different media, streams and conditions require the use different measurement methods.

Measurement of dissolved oxygen concentration in laboratories is performed by Winckler's method or method of iodometric titration (Guidance document 52.24.419-2005. Mass concentration of dissolved oxygen in water. Method of performing measurements by iodometric method). Despite the fact that Winckler's method is considered to be standard chemical method for solutions analysis with its multiple modifications simplifying studies, it is not possible to use it for operational express-analysis in field conditions (Erke, Kostina, Bondar et al., 2018). Therefore for operational measurement of dissolved oxygen concentration in water during the project analyzers of dissolved oxygen or oxymeters were used (Figure 4 A, C), as well as special test-kits for express determination of dissolved oxygen (visual colorimetric method, Figure 4 B).

After analysis of analytical instruments and consultations with manufacturers it was decided to use only devices based on more neutral method – amperometric method.

The principle of amperometric analyzer for dissolved oxygen is based on electrochemical method for measurement of oxygen concentration.

Number of portable devices and two types of analytical instruments are used in the project for different ranges of measurement (from close to



A B C

Figure 4. Laboratory methods for measurement of oxygen concentration. A – Portable flow-type analyzer MARK-3010, B – test-kits Chemetrics, C – portable flow-type analyzer MARK-302T.

balanced concentration values to insignificant values of several mkg/l).

Selected express-methods for measurement of oxygen by visual colorimetric methods are also used for verification: Indigo blue carminic for values of at least 1 mg/l and Rodhazine D for values in mkg/l (ASTM D 888-87, Dissolved Oxygen in Water; ASTM D5543-09, Standard Test Methods for Low-Level Dissolved Oxygen in Water) (Figure 4).

For complete control over oxygen concentration at various stages of ASP process scheme a number of sampling points were designed and arranged, as well as flow-type analytical measuring instruments.

Green boxes in simplified diagram (Figure 5) of the process show sampling points, and yellow boxes – spots of oxygen control with flow-type analytical instruments, red arrow indicates spot of oxygen scavenger supply.

Such number of control points of oxygen concentration allows to promptly identify reasons of concentration increase (oxygen sources), and use of three approaches to determination (portable instrument – test-kit – instrumentation) minimizes probability of wrong determination of oxygen concentration. In addition, special focus is made on determination of excess of sulfite-ions in various media, as indication of processes occurring in them. Absence of sulfites can become a signal for quick increase of oxygen level (Erke, Kostina, Bondar et al., 2018). It is particularly important to have an excess of chemical before mixing with isobutyl alcohol or other liquid, in which oxygen solubility can be significantly higher than in water.

Also, implementation of scheme with nitrogen blanketing of tank equipment allows to make a conclusion that process media should be protected after introduction of chemical scavenger or introduction of polymer into the process. That means that there is no need to make nitrogen blanketing in source water tanks, intermediate tanks of water treatment unit, etc.; which will allow to reduce operational expenditures.

Conclusions and recommendations

During implementation of ASP technology where one of the key roles is played by control over oxygen dissolved in water and solutions, it is important to take into account a number of factors and implement the following recommendations (Erke, Kostina, Bondar et al., 2018):

- At design stage it is required to exclude contact with atmospheric air by means of maintenance of nitrogen blanketing in tank equipment, especially for deoxygenated media, because the system will quickly return to balanced concentration of oxygen in water or water solution, which is mg/l units. There is no need to make nitrogen blanketing in tanks with source water, intermediate tanks of water treatment unit, etc.; this will allow to reduce OPEX.
- It is required to maintain excess of oxygen scavenger at acceptable level. Lack of excess is a signal of problem and increase of oxygen level in near future, big excess also can be the cause of polymer degradation;
- It is required to comply with water-chemical mode for application of chemical scavenger which means maintenance of optimal temperature, pH and residence time;

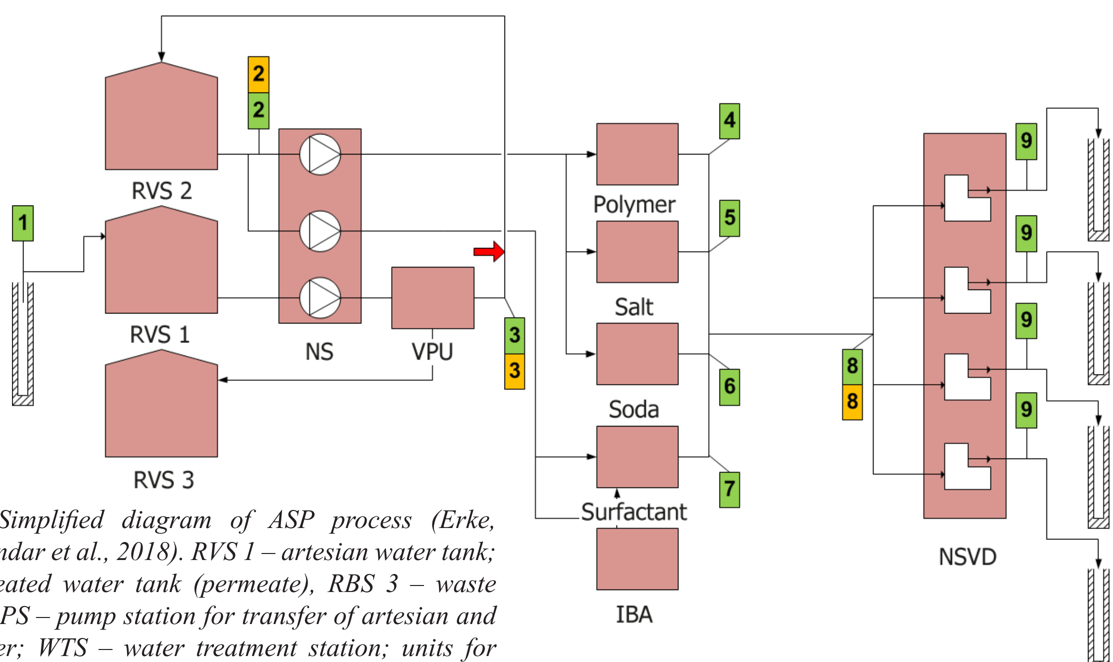


Figure 5. Simplified diagram of ASP process (Erke, Kostina, Bondar et al., 2018). RVS 1 – artesian water tank; RVS 2 – treated water tank (permeate), RBS 3 – waste water tank; PS – pump station for transfer of artesian and treated water; WTS – water treatment station; units for preparation of mother solutions of chemicals (polymer, salt, soda, surfactant, isobutyl alcohol); HPPS – high pressure pump station for injection of ASP solutions into the reservoir. Flows of media in which analysis of dissolved oxygen concentration is performed are marked with figures: 1 – Artesian water; 2 – Treated water (permeate) downstream of RVS tank; 3 – Treated water (permeate) upstream of RVS tank; 4 – Polymer mother solution; 5 – Salt mother solution; 6 – Soda calcinated mother solution; 7 – Surfactant and isobutyl alcohol mother solution; 8 – ASP mixture at inlet point of injection pump station after mixing; 9 – Sampling points on injection line of high pressure pumps.

• It is required to take into account oxygen ingress with ASP components, especially those in which oxygen solubility is abnormally high;

• It is important to understand what methods of oxygen concentration measurement are applicable and optimal for different media, especially multi-component media, for this purpose it is required to consider side physical and chemical processes which may result in wrong measurement of oxygen concentration. Also, the use of different alternative methods will be useful for verification;

• Special focus should be made on development of sampling points system and their arrangement in order to exclude contact with atmosphere in process of sampling and compliance with sampling rules;

• When selecting a chemical method it is important to select the chemical, which application will not lead to additional actions for implementation of optimal water-chemical modes.

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The results interpretation of thermogasdynamic studies of vertical gas wells incomplete in terms of the reservoir penetration degree

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Abstract. A method is proposed for interpreting thermogasdynamic studies of vertical gas wells that are incomplete in terms of the reservoir penetration degree on the basis of inverse problem theory. The inverse problem has the aim to determine the reservoir parameters for nonisothermal filtration of a real gas to a vertical well in an anisotropic reservoir. In this case, the values of the pressure and temperature at the well bottom, recorded by deep instruments, are assumed to be known. The solution of the inverse task is to minimize the functional. The iterative sequence for minimizing the functional is based on the Levenberg-Marquardt method. The convergence and stability of the iterative process for various input information have been studied on specific model examples. The effect of reservoir anisotropy on the pressure and temperature changes at the bottom of the well is studied. It is shown that if the reservoir is not completely penetrated by the results of pressure and temperature measurements at the bottom of the well after its start-up, anisotropy of the reservoir can be estimated. It should be noted that when studying thermodynamic processes in the vicinity of a well, which penetrates thick layers, it is necessary to take into account not only the heat exchange of the reservoir with the surrounding rocks, but also the geothermal temperature gradient.

Keywords: anisotropy, thermogasdynamic studies, incomplete well

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Introduction

Most of the gas fields have a layered structure, due to the peculiarities of the sedimentation process. In layered reservoirs, the filtration properties in the plane of the layers differ from the filtration properties in the direction perpendicular to the layers, i.e. such reservoirs are anisotropic. In real gas reservoirs, anisotropy can be caused by fracturing, layering, the presence of various inclusions, which lead to unequal properties of the medium in different directions.

The heterogeneity of the formation in the vertical and horizontal directions is characterized by the anisotropy parameter. The parameter of reservoir anisotropy is of decisive importance in predicting the technological regime of wells operation, exposing reservoirs with bottom water, multi-layer deposits, etc. In work (Gritsenko et al., 1995), a grapho-analytical method is suggested for estimating anisotropy based on the results of gas-hydrodynamic studies of vertical wells that are incomplete in terms of the reservoir penetration degree. The incompleteness of the bottom entails the appearance of additional filtering resistances arising in the bottomhole zone and a decrease in production rates as a result of the deviation in the liquid flow geometry from the flat-radial flow (Basniev et al., 1993; Gritsenko et al., 1995; Korotaev et al., 1991; Masket, 1949; Shchurov, 1983). In this regard, consideration of the characteristics of the inflow to incomplete wells is of great practical importance.

In this paper, we propose a method for interpreting thermogasdynamic studies of vertical gas wells that are incomplete in terms of the reservoir penetration degree on the basis of the inverse problem theory. The effect of anisotropy on the pressure and temperature changes at the bottom of the well is investigated. It is shown that the results of pressure and temperature measurements at the bottom of the well after its start-up can be used to evaluate the anisotropy of the reservoir.

Nonisothermal gas filtration in an anisotropic reservoir

Thermogasdynamic methods for studying gas wells are based on the processes of pressure and temperature redistribution in the reservoir when they are put into operation and after a stop. The process of non-isothermal filtration of a real gas to a vertical well in an anisotropic reservoir is described by a system of differential equations:

$$m\frac{\partial}{\partial t}\left(\frac{p}{T\varsigma}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{k_r}{\mu}\frac{p}{T\varsigma}r\frac{\partial p}{\partial r}\right)+\frac{\partial}{\partial z}\left(\frac{k_z}{\mu}\frac{p}{T\varsigma}\frac{\partial p}{\partial z}\right),$$

$$r\in(r_w,R_k),\ z\in(0,L),\ t>0, \quad (1)$$

$$C_1\frac{\partial T}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_1\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda_1\frac{\partial T}{\partial z}\right)+$$

$$C_p\frac{p}{RT\varsigma}\left(\frac{k_r}{\mu}\frac{\partial p}{\partial r}\left[\frac{\partial T}{\partial r}-\varepsilon\frac{\partial p}{\partial r}\right]+\frac{k_z}{\mu}\frac{\partial p}{\partial z}\left[\frac{\partial T}{\partial z}-\varepsilon\frac{\partial p}{\partial z}\right]+m\eta\frac{\partial p}{\partial t}\right),$$

$$r\in(r_w,R_k),\ z\in(0,L),\ t>0, \quad (2)$$

with initial

$$p(r,z,0)=p_0,\ r\in(r_w,R_k),\ z\in(0,L), \quad (3)$$

$$T(r,z,0)=T_0+(L-z)G,\ r\in(r_w,R_k),\ z\in(0,L), \quad (4)$$

and boundary conditions:

$$2\pi\int_{L-L_w}^{L}\left[\frac{k}{\mu}\frac{pT_{st}}{p_{st}T\varsigma}r\frac{\partial p}{\partial r}-\frac{C_w}{L_w}\frac{\partial}{\partial t}\left(\frac{p}{T\varsigma}\right)\right]_{r=r_w}dz=Q,$$

$$z\in[L-L_w,L], \quad (5)$$

$$\left[C_1\frac{\partial T}{\partial t}-C_p\frac{p}{RT\varsigma}\left(\frac{k}{\mu}\frac{\partial p}{\partial r}\left[\frac{\partial T}{\partial r}-\varepsilon\frac{\partial p}{\partial r}\right]\right)-\right.$$

$$\left.-C_p\frac{p}{RT\varsigma}\left(m\eta\frac{\partial p}{\partial t}\right)\right]_{r=r_w}=0,\ z\in[L-L_w,L], \quad (6)$$

$$\left.\frac{\partial p}{\partial r}\right|_{r=r_w}=0,\ z\in[0,L-L_w), \quad (7)$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=r_w}=0,\ z\in[0,L-L_w), \quad (8)$$

$$p(r_k,z,t)=p_0,\ z\in[0,L],\ t>0, \quad (9)$$

$$T(r_k,z,t)=T_0+(L-z)G,\ z\in[0,L],\ t>0, \quad (10)$$

$$\left[\frac{\partial p}{\partial z}\right]_{z=0}=\left[\frac{\partial p}{\partial z}\right]_{z=L}=0,\ r\in(r_w,R_k),\ t>0, \quad (11)$$

$$\left[\frac{\partial T}{\partial z}\right]_{\substack{z=0\\z=L}}=\sqrt{\frac{\lambda_2C_2\rho_2}{\pi t}}\left(T-T\big|_{\substack{z=0-\xi(t)\\z=L+\xi(t)}}\right)\ \text{или}$$

$$\left[\frac{\partial T}{\partial z}\right]_{\substack{z=0\\z=L}}=0,\ r\in(r_w,R_k),\ t>0 \quad (12)$$

where L – the thickness of the reservoir, L_w – the depth of the reservoir penetration, μ – the gas viscosity, m – the reservoir porosity, p_0, T_0 – the pressure and temperature at the reservoir boundary, p_{st}, T_{st} – the standard pressure and temperature, r_w, R_k – the radii of the well and external boundary, Q – the well production rate, z – the gas supercompressebility, k_r, k_z – the reservoir permeability along the directions of r and z axes, η – the adiabatic expansion factor, ε – the Joule-Thomson coefficient, $C_1=mC_p\,p/RT\varsigma+(1-m)C_2\rho_2$ – the volumetric heat capacity of the reservoir, C_p, C_2 – the specific heat capacity of the gas and medium, p_2 – the medium density, R – the gas constant, λ_1, λ_2 – the thermal conductivity of the gas and medium, C_w – wellbore storage coefficient, G – geothermal gradient. The first expression of condition (12) simulates the process of heat exchange on the roof and the bottom of the gas reservoir by rocks, i.e. non-thermal insulated reservoir. Conditions (5) – (8) simulate the process of heat and mass transfer to a vertical well that is incomplete in the degree of reservoir penetration.

Zone of thermal compensation above the roof and below the bottom of the formation is calculated by the formula:

$$\xi(t)=\sqrt{\pi\frac{\lambda_2}{C_2\rho_2}t}\,.$$

The wellbore storage coefficient is calculated by the formula (Korotaev et al., 1991; Khairullin et al., 2013, Shamsiev, Talipova, 2015). The gas supercompressibility coefficient ζ is calculated by the formula of Gurevich-Latonov (Bondarev et al., 1988). The adiabatic expansion coefficient η and the Joule-Thomson coefficient ε are calculated by the formulas (Korotaev et al., 1991).

Equations (1) – (12) belong to the class of quasilinear parabolic equations. The greatest difficulty is the numerical solution of equation (2), which simultaneously describes conductive and convective heat transfer, including the Joule-Thomson effect, as well as a decrease in the gas temperature due to its adiabatic expansion. For the numerical solution of the system (1) – (12), the finite difference method is applied. The solution area is covered by a non-uniform grid, which thickens at the approach to the well.

Results of the calculations

In the case of model examples, influence the reservoir anisotropy on pressure and temperature curves at the bottom of the well is studied. A model reservoir with the following data is considered: H = 20 m, R_k = 250 m, r_w = 0.1 m, p_0 = 20 MPa, T_0 = 300 K, T_{st} = 293 K, μ = 0.012 mPa s, m = 0.2, k_r = 0.01 мкм^2, C_p =2093 J/ kg K, C_2 = 920 J/ kg K, r_2 = 2700 kg / m^3, R = 520 J/kg K, λ_1 = 1.52 W/m K, λ_2 = 1.9 W/m K, G = 0.01 K/m, Q = 500 thousand m^3/day, operation time of the well t_{exp} = 5 days.

From the results obtained, it follows that the process of heat exchange of the reservoir with surrounding rocks affects the temperature field and has little effect on the pressure field in the reservoir. It should be noted that when studying thermodynamic processes in the vicinity of a well, which penetrates thick layers, it is necessary to take into account not only the heat exchange of the reservoir with the surrounding rocks, but also the geothermal temperature gradient. Comparison of the numerical solution of the system (1) – (12) with the numerical solution of the one-dimensional task (Shamsiev, Talipova, 2015) at $G = 0$, $k_r = k_z$ is shown in Figure 1. Deviations of the final sections of the derivatives of the bottomhole temperature curves are observed. This is due to the process of heat exchange with surrounding rocks. In the case of a thermally insulated reservoir, numerical solutions of one-dimensional and two-dimensional tasks almost coincide.

Figure 2 shows curves of bottomhole pressure, temperature and their derivatives depending on the

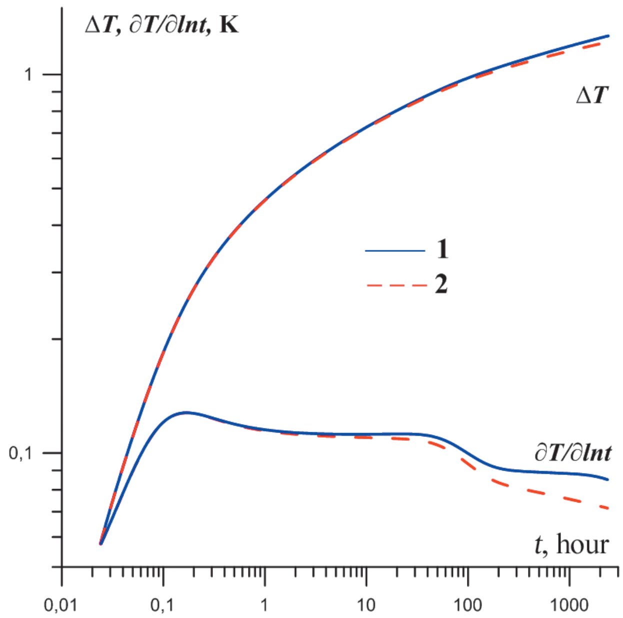


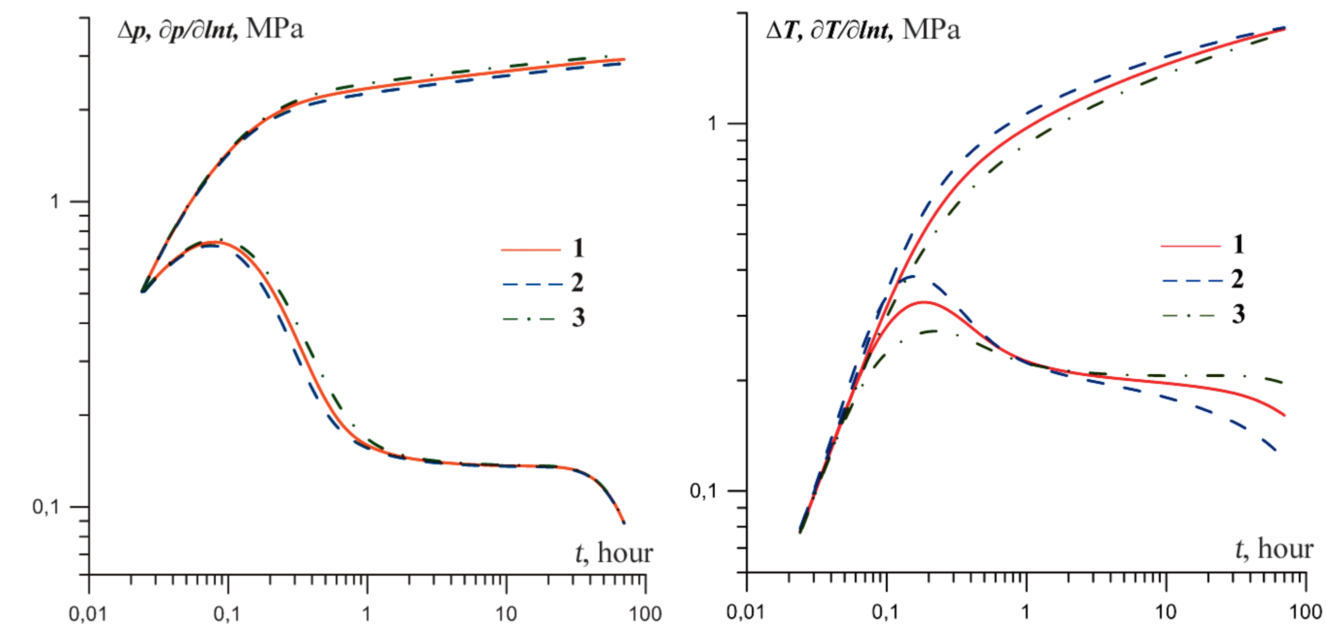
Figure 1. The bottomhole temperature curve and its derivative. The reservoir is completely penetrated and not thermally insulated, $G = 0$. $k_r = k_z$. 1 – numerical solution of system (1) – (12), 2 – numerical solution of one-dimensional task.

reservoir anisotropy after the well has been put into operation without full penetration. The calculations were carried out at $k_r = k_z = 0.01$ μm^2; $k_r = 0.01$ μm^2, $k_z = 0.02$ μm^2; $k_r = 0.01$ μm^2, $k_z = 0.005$ μm^2. When launching a vertical well with a constant production rate and incomplete penetration of the reservoir, the initial radial, spherical and late radial flows are observed. The initial radial flow is masked by the presence of the influence of the borehole volume (Figure 2). The negative slope of the derivative curve characterizes the presence of a spherical flow. The less the reservoir is penetrated, the longer the duration of the spherical flow. The straight section on the pressure derivative curve is the diagnostic sign of the late radial flow (Figure 2). The deviations of the final sections of the pressure and temperature curves characterize the influence of the reservoir boundary.

The results of calculations showed that the less the reservoir is penetrated, the more sensitive the pressure and temperature curves to variations in the permeability coefficients k_r, k_z.

Evaluation of the reservoir anisotropy

The results interpretation of thermogasdynamic studies of gas wells is based on the solution of the inverse problem. As the initial information, the data on the change in bottomhole pressure and temperature, recorded by deep instruments after the start-up of the well, are used. The aim of the inverse task is to determine the permeability coefficients k_r, k_z and the porosity of the reservoir m, when the process of non-isothermal filtration of a real gas to a vertical well incomplete in the degree of reservoir penetration is described by the system of equations (1) – (12).



a) b)

Figure 2. Curves of pressure (a), temperature (b) and their derivatives. The reservoir is penetrated by 50%. 1 – $k_r = k_z$, 2 – $k_r < k_z$, 3 – $k_r > k_z$

The following initial information is considered known:

$$p(r_w, L, t) = \phi(t),\ T(r_w, L, t) = \psi(t), \qquad (13)$$

where $\phi(t)$, $\psi(t)$ – observed values of pressure and temperature at the bottom of the well.

The solution of the inverse problem (1) – (12) and (13) is to minimization the functional (Khairullin et al., 2013, Shamsiev, Badertdinova, 2012; Shamsiev, Talipova, 2015):

$$F(\alpha) = \int_0^{t_{exp}} \left\{ \xi[\phi(t) - p(r_w, L, t)]^2 + [\psi(t) - T(r_w, L, t)]^2 \right\} dt, \qquad (14)$$

where $\alpha = (k_r, k_z, m)$, $0 < a_i \leq \alpha_i \leq b_i$ (a_i, $b_i = const$), ξ – weighting parameter.

The iterative sequence for minimizing the functional (14) is based on the Levenberg-Marquardt method. The convergence and stability of the iterative process with different input information have been studied using standard madel examples. The iterative process is considered to be completed when one of the specified precision is reached (10^{-6} – for the functional, 10^{-6} – for the gradient, 10^{-6} – for the argument) or when performing a specified number of iterations ($N_{iter} = 40$). For exact values of the initial information, the iterative process of minimizing the functional (14) converges in 6-8 iterations. To study the stability in the model curves, changes in bottomhole pressure and temperature randomly introduced errors, where $\phi_{\delta_1}(t) = \phi(t) + \omega\delta_1$, $\psi_{\delta_2}(t) = \psi(t) + \omega\delta_2$, where δ_1 = 0.05 MПa, δ_2 = 0.05 K, ω – a random variable distributed along a uniform law on the interval [-1, 1]. With the perturbed initial data, the iterative process of minimizing the functional (14) converges for 10-15 iterations. The results of the calculations show that the proposed method is stable with respect to the errors of the initial information.

Figure 3 shows one of the characteristic calculations of the convergence of the iterative process of minimizing the functional (13) with the perturbed initial data

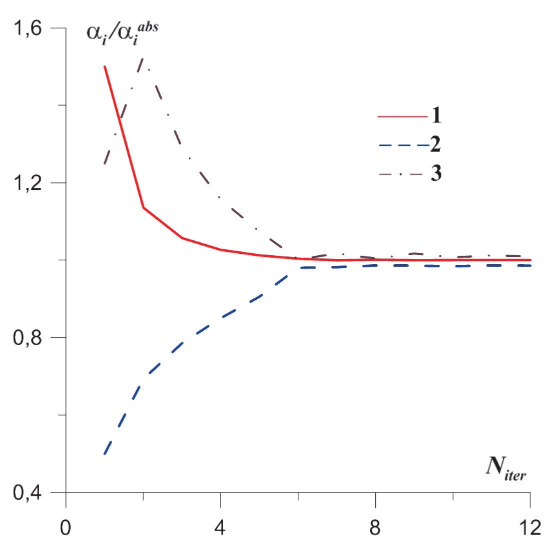


Figure 3. Convergence of the iterative process. 1 – k_r, 2 – k_z, 3 – m

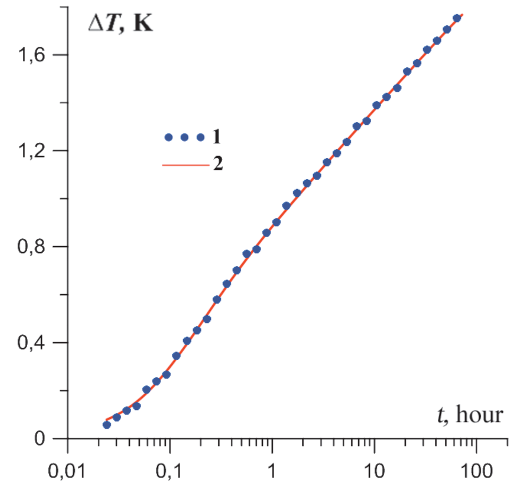


Figure 4. Curves of temperature changes. The reservoir is penetrated by 50%. 1 – perturbed, 2 – calculated curves

(Figure 4, curve-1), where α – true parameters, α_i^{abs} – calculated parameters. The calculated temperature curves are shown in Figure 4 (curve-2). The iterative process converges in 12 iterations.

From the results obtained, it follows that when the reservoir is partially penetrated by the results of thermogasdynamic studies of gas wells, anisotropy of the reservoir can be estimated.

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Modeling of non-stationary fluid inflow to a multisectional horizontal well

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Abstract. For a more uniform production of oil reserves, horizontal wells are equipped with intelligent completion systems with remotely controlled multisection inflow control equipment and sensors to monitor pressure and temperature. A new semi-analytical solution of the problem of non-stationary fluid inflow to a multisectional horizontal well in an anisotropic reservoir is obtained. Typical curves of the pressure and pressure derivative in the isolated sections of the horizontal wellbore are built, taking into account the skin factor and the effect of the wellbore volume. It is shown that, for isolated sections of the horizontal wellbore with the help of profile reservoir separators and packers, the pressure response in inactive sections occurs with a delay. At the same time, inactive sections have little effect on the pressure change in the active section. With the decrease in the length of the reservoir uncouplers, the mutual influence of the active and inactive sections is strengthened. The effect of the fluid "crossflow" through the inactive sections of the horizontal wellbore has been revealed. A similar effect of fluid "crossflow" is observed in the trunk of a horizontal well after its stopping, as well as in the intervals of penetration by the stopped imperfect vertical well.

Keywords: multisectional horizontal well, intelligent well, semi-analytical solution, non-stationary inflow, pressure curve, skin factor, fluid "crossflow" effect

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At present, in the development of oil and gas fields with hard-to-recover reserves, horizontal drilling technology is widely used. The main advantage of drilling horizontal wells (HW) is an increase in the drainage area due to the expansion of the contact area with the reservoir. The length of the trunk can reach several hundred meters, and in some cases several kilometers. To more evenly produce oil reserves in heterogeneous formations, the horizontal wells are equipped with intelligent completion systems with remotely controlled multisectional inflow control equipment and sensors to monitor the pressure and temperature in each section. Figure 1 shows one of the schemes for separating a horizontal well into a section with electrically controlled inflow control valves developed at Tatneft PJSC. To isolate the sections from one another, profile strippers of lengths of 15-20 m and expandable packers are used. Separation of a horizontal trunk into sections with the possibility of cutting off sections as they are watered increases the manageability of the mining and reduces operating costs (Takhautdinov et al., 2013; Abdrakhmanov et al., 2017; Sagidullin et al., 2017).

Due to the fact that intelligent horizontal wells are becoming more common, the current task is to develop a methodology for interpreting the results of hydrodynamic studies of such wells in order to determine the reservoir's filtration parameters and optimal operating conditions. Graphoanalytical methods for interpreting the results of hydrodynamic researches of HW are based on the analysis of diagnostic pressure and pressure derivative graphs from the logarithm of time. On the diagnostic charts, separate regimes of fluid flow to the HW trunk and the parameters of the reservoir and well are determined from the angle of inclination of the pressure-change curve in the corresponding coordinates: vertical and horizontal permeability of the reservoir, skin effect and effective length of the horizontal trunk. Often on diagnostic charts, the initial radial and linear modes of fluid flow to the HW are masked by the effect of the volume of the wellbore. The horizontal permeability of the reservoir is determined by the late pseudo-radial flow regime to the HW, the time of its development depends on the length of the wellbore and may be longer than the time of the well investigation.

In work (Frick et al., 1996) a method of hydrodynamic researches of HW in isolated segments was proposed, which makes it possible to determine the permeability and local skin factor in the tested intervals of the HW.

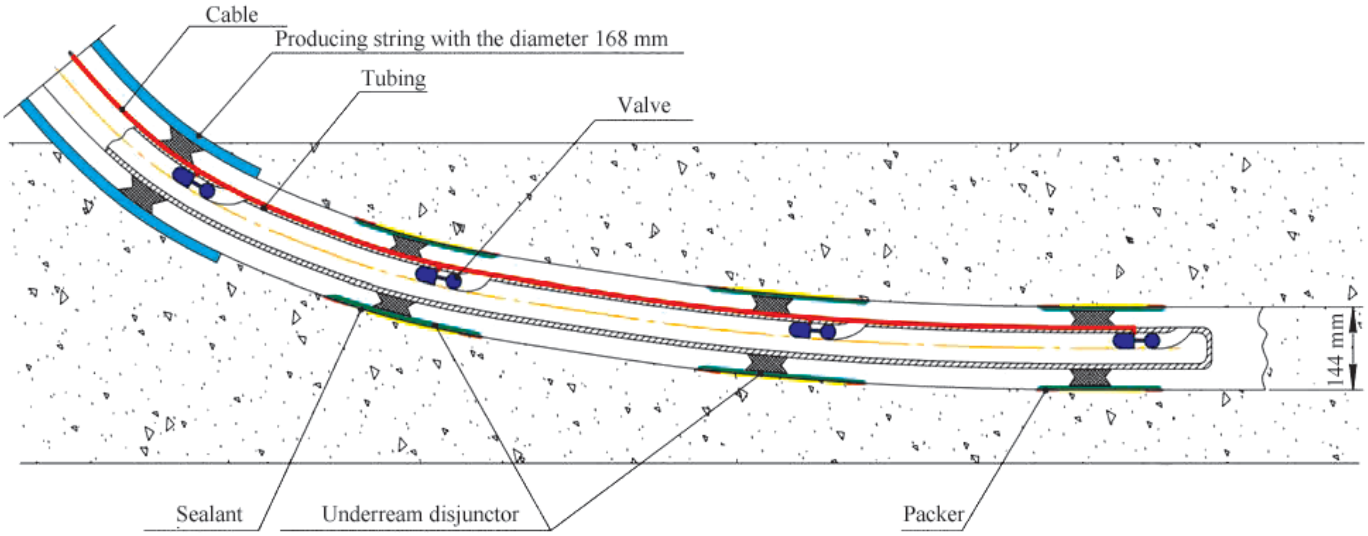


Figure 1. Scheme of multi-sectional HW with electrocontrolled flow control valves (Takhautdinov et al., 2013)

It is shown that from the pressure measurements in the HW segments isolated from the tested interval by means of packers, it is possible to obtain additional information on the permeability of the formation. Analytical solutions are presented in (Kamal et al., 1993; Yildiz et al., 1994; Rbeawi et al., 2014; Li et al., 2016; He et al., 2017) of the non-stationary inflow of liquid to a horizontal well with several production intervals. In the works (Kamal et al., 1993, Yildiz et al., 1994) it is noted that hydrodynamic research methods do not allow to obtain information on the number and length of inflow intervals to the HW, and geophysical methods should be used to extract them. In the works (Muslimov et al., 2003; Morozov et al., 2007) a technique is proposed for interpreting the pressure curves taken simultaneously at different sections of the horizontal wellbore.

In the present paper, a new semi-analytical solution is obtained for the problem of non-stationary fluid flow to a multisectional horizontal well. The principal difference of this solution from the known analytical solutions, for example, presented in the works (Kamal et al., 1993, Yildiz et al., 1994; He et al., 2017), is the account of the isolation of HW sections from each other with the help of seam breakers and packers. Another equally important difference is the consideration of the uniform pressure distribution in the sections of the HW. On the basis of the solution obtained, the effect of opening and closing the inflow control valves on the pressure and pressure derivative curves in isolated sections of the HW trunk is analyzed.

A semi-analytical solution of the problem

Let us assume that the anisotropic reservoir has an impenetrable roof and a bottom, and is unrestricted along its strike. We direct the x axis along the HW trunk, and the z axis vertically upwards (Figure 2).

Let the HW trunk be divided into N sections and a liquid with constant production rate Q be taken from the k-th section. We assume that the pressure distribution in each section of the HW trunk is uniform, i.e. (equation). To solve the problem, we use the solution for a point source in an anisotropic reservoir, bounded by two parallel impermeable planes (Ozkan et al., 1991). By integrating elementary sources with a flow density q along the sections of the HW, taking into account the assumption of a uniform pressure distribution on the cylindrical surfaces of sections, we obtain a system of integral equations for determining the Laplace image of the pressure functions $p_i(t)$ and the fluid flow distribution $q_i(x, t)$ along the length of the sections of the HW (Morozov, 2017):

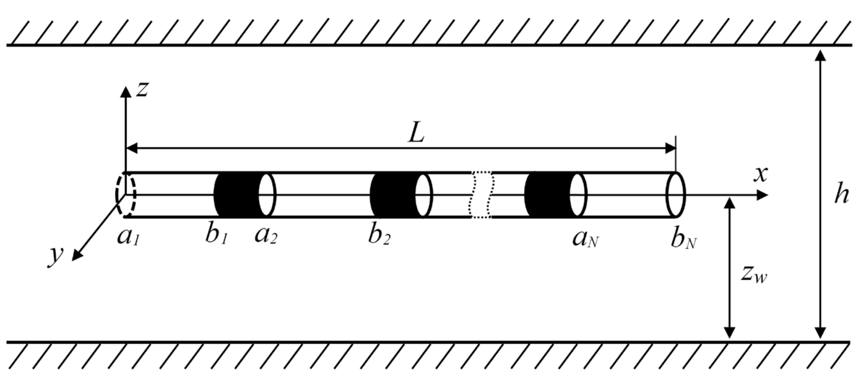


Figure 2. Scheme of the reservoir, penetrated by a multisectional horizontal well

$$\overline{p}_{id}(u) = S_i l_{di}\overline{q}_i(x_d,u) + \frac{1}{2}\sum_{j=1}^{N}\int_{a_{dj}}^{b_{dj}}\overline{q}_j(x_d,u)\Big[K_0\left(\sqrt{u}|x_d - x'|\right) +$$

$$+ 2\sum_{n=1}^{\infty}K_0\left(\sqrt{u+\xi_n^2}|x_d - x'|\right)\cos\xi_n z_{wd}\cos\xi_n(z_{wd}+r_{cd})\Big]dx',$$

$$x_d \in (a_{di}, b_{di}),\ i = \overline{1,N} \quad (1)$$

$$\int_{a_{di}}^{b_{di}}\overline{q}_i(x',u)dx' = \begin{cases}\frac{1}{u} - C_{id}u\overline{p}_{id}(u),\ i = k,\\ -C_{id}u\overline{p}_{id}(u),\ i \neq k.\end{cases} \quad (2)$$

where u – the Laplace transform variable;

$p_{id} = \frac{2\pi k_h h(p_k - p_i(t))}{\mu Q}$ – the non-dimensional pressure in the i-th section of the HW trunk; $l_{di} = b_{di} - a_{di} = (b_i - a_i)/L$ – the dimensionless length of the i-th section; p_k – the reservoir pressure; $t_d = \frac{k_h t}{\mu\beta^* L^2}$ – dimensionless time; k_v, k_h – vertical and horizontal permeability; β^* – the elastic capacity of the reservoir; μ – the viscosity; $C_{id} = \frac{C_i}{2\pi h\beta^* L^2}$ – dimensionless coefficient of influence of the volume of the i-th section of the HW trunk; S_i – skin factor of the i-th section;

$$x_d = \frac{x}{L};\quad \xi_n = \frac{\pi n}{h_d};\quad h_d = \sqrt{\frac{k_h}{k_v}}\frac{h}{L};$$

$$r_{cd} = \frac{r_c}{2L}\left(1 + \sqrt{\frac{k_h}{k_v}}\right);\quad z_{wd} = \sqrt{\frac{k_h}{k_v}}\frac{z_w}{L};$$

$K_0(z)$ – a modified Bessel function of the second kind of the 0-th order. The skin factor S_i characterizes the additional filtration resistance in the near wellbore zone of the i-th section of the HW trunk. Since the sections are isolated from one another, $C_i = \beta V_i$, where β is the fluid compressibility, V_i is the volume of the i-th section of the HW trunk.

We note that for N = 2, the system of integral equations (1) – (2) is also a solution of the problem of interference of active and observable horizontal wells of length l_1 and l_2, respectively, whose axes lie on one straight line. In contrast to the solutions of the analogous problem presented in the works (Malekzadeh et. al., 1991; Al-Khamis et. al., 2005; Awotunde et. al., 2008), decision (1) – (2) is taken into account skin factor and the effect of the volume of the trunks of active and observational horizontal wells.

In the event that liquid is withdrawn not from one section but simultaneously from several sections of the HW (the inflow control valves in these sections are open), we assume that the pressure in the respective sections is uniformly distributed. Let, for example, a liquid with a constant production rate Q be selected from sections of the HW with indices from the set I. Then, instead of (2), we write:

$$\sum_{i\in I}\int_{a_{di}}^{b_{di}}\overline{q}_i(x',u)dx' = \frac{1}{u} - C_d u\overline{p}_d(u),$$

$$\int_{a_{di}}^{b_{di}}\overline{q}_i(x',u)dx' = -C_{id}u\overline{p}_{id}(u),\ i \notin I, \quad (3)$$

where $p_d = p_{id}$, $i \in I$ is the dimensionless pressure in the active sections of the HW trunk, C_d is the dimensionless coefficient of influence of the volume of the active sections of the HW trunk.

Let us suppose now that all inflow control valves are open and fluid is withdrawn from all sections of the HW with a constant production rate Q. We will assume that in this case the sections of the HW trunk are not isolated from each other and the pressure in the sections is evenly distributed. Then the system of integral equations (1), (3) is a solution of the problem of non-stationary fluid inflow to a horizontal well with several production intervals. A similar solution of the problem was obtained in a paper (Li et al., 2016), in contrast to the works (Kamal et al., 1993; Yildiz et al., 1994; He et al., 2017), where it was assumed that the inflow of liquid to the production intervals is uniformly distributed.

In case of dual operation of the multi-sectional HW, when the selection of fluid from each section is independent, equations (2) must be replaced by equations

$$\int_{a_{di}}^{b_{di}}\overline{q}_i(x',u)dx' = \frac{\alpha_i}{u} - C_{id}u\overline{p}_{id}(u),\ i = \overline{1,N}, \quad (4)$$

where $\alpha_i = \frac{Q_i}{Q}$ – is the share of the i-th section in the total producton rate of multisectional HW $Q = \sum_{i=1}^{N}|Q_i|$, Q_i – the production rate of the i-th section, $\sum_{i=1}^{N}|\alpha_i| = 1$.

If we put N = 2 in the system of integral equations (1), (4), we obtain a solution to the problem of interference of two sections of the HW or two operational horizontal wells whose axes lie on the same straight line.

For the numerical solution of systems of integral equations (1) – (2), (1), (3) or (1), (4), each section of the HW trunk is divided into segments and it is assumed that the inflow of liquid to the segments is uniform. Substituting the coordinates of the segment centers instead of xd, we obtain a system of algebraic equations for determining the Laplace image of the functions of changing the pressure and fluid flow to the sections of the HW trunk. The originals of the inflow and pressure functions are numerically based on the Stefest algorithm, which requires a multiple solution of a system of linear algebraic equations with a dense matrix. To solve this problem, we use a stabilized method of BiCGStab bi-conjugate gradients with preconditioning.

Results of calculations

As an example, the problem of non-stationary fluid flow to a horizontal well in an anisotropic layer is considered, the trunk of which is divided into three sections. The calculations were carried out with the following initial data: L = 300 m, h = 20 m, z_w = 10 m, a_1 = 0 m, b_1 = 100 m, a_2 = 120 m, b_2 = 200 m, a_3 = 220 m, b_3 = 300 m, k_h = 0.1 μm², k_v = 0.01 μm², μ = 10 mPas, β^* = 1·10⁻⁴ MPa⁻¹, Q = 20 m³/day, C_1 = 0.1 m³/ MPa, C_2 = 0.01 m³/MPa, C_3 = 0.01 m³/MPa, S_1 = 0, S_2 = 1, S_3 = 0.5. With numerical realization of the problem solution, each section of the HW trunk was divided into 10 uniform segments.

In the first example, it is assumed that a horizontal well is put into operation with a constant production rate Q when all inflow control valves are open. In this case, the pressure along the HW trunk is distributed uniformly ($p_1 = p_2 = p_3$), with the inflow of fluid moving along the entire trunk, except for the areas covered by the reservoir uncouplers. Figure 3a shows the pressure and pressure derivative curves in the HW, and Figure 3b – the distribution of fluid flow along the trunk of the HW at the final moment of time. The slight asymmetry of the fluid flow along the HW stem is due to the difference in the skin factor in the individual sections of the HW trunk.

In the following example, it is assumed that only the first inflow control valve is open. Figure 4a shows the pressure and pressure derivative curves in sections of the HW trunk. For comparison, Figure 4, and the symbols show the results of calculations of pressure and pressure derivative in a HW with a trunk length of 100 m, obtained in the "Saphir" package of KAPPA Engineering. An analysis of the pressure derivative in

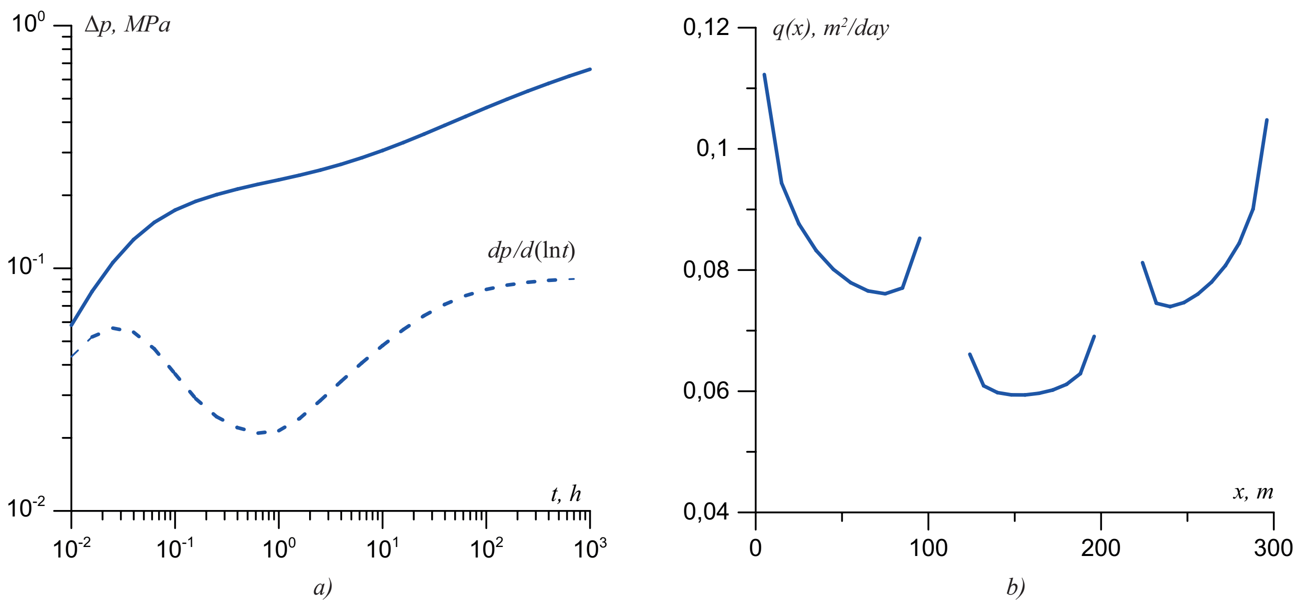


Figure 3. Pressure and pressure derivative curves (a) and distribution of fluid flow along the HW trunk (b), all valves are open

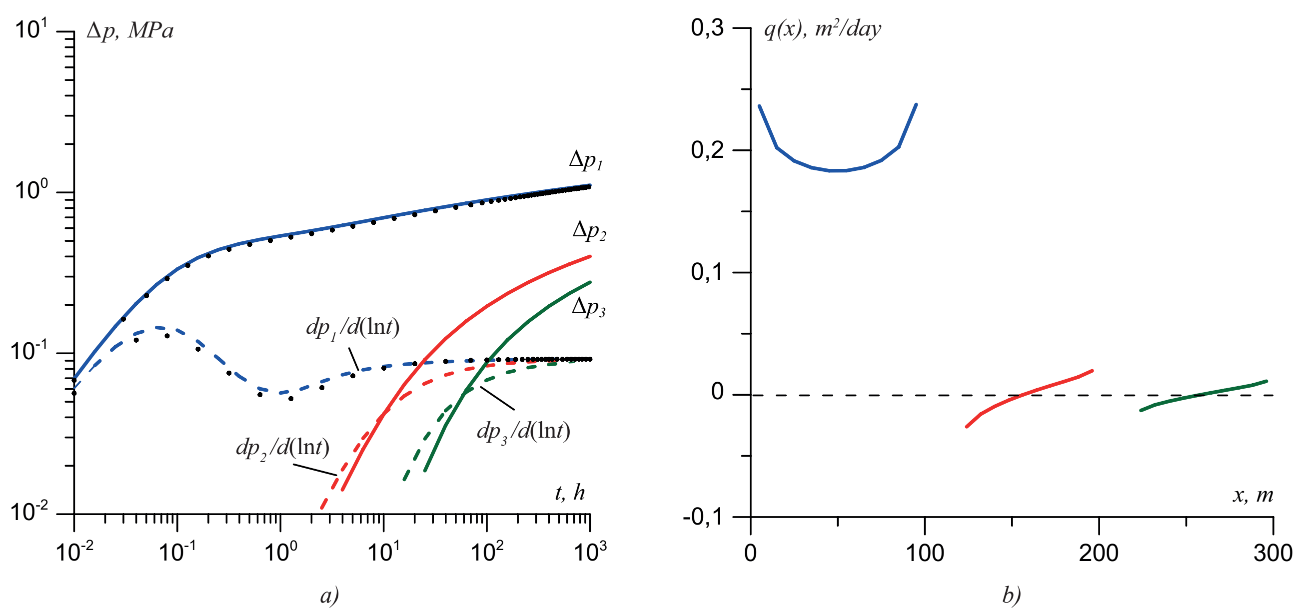


Figure 4. Pressure and pressure derivative curves (a) and distribution of fluid flow along the HW trunk (b), the first valve is open

the active section of the HW trunk showed that, due to a decrease in the operating length of the HW, the time to reach the late radial flow regime is almost an order of magnitude lower than in the previous example. Since the sections are isolated from each other by profile breakers and packers, the pressure response in the inactive sections of the HW trunk occurs with a delay, and for the third section the pressure response time is the longest, and the amplitude of the pressure change is smaller. Inactive sections of the HW trunk have little effect on the pressure change in the active section. With the decrease in the length of the layer uncouplers, the mutual influence of the active and inactive sections will be strengthened.

Figure 4b shows a graph of the distribution of the liquid inflow to the sections of the HW at the final moment of time. It can be seen that fluid flow through the inactive sections of the HW trunk. This effect is explained by the fact that sections of the HW trunk are channels of "infinite conductivity" and a part of the liquid in the reservoir flows along the path of the least filtration resistance. Thus, inactive sections of the HW simultaneously inflow of liquid from the formation and outflow of liquid into the reservoir, and for large times the total inflow and outflow is zero. It should be noted that the effect of fluid "overflow" also occurs in the trunk of the observation horizontal well with interference from two horizontal wells (Malekzadeh et al., 1991; Al-Khamis et al., 2005; Awotunde et al., 2008). In addition, this effect is observed in the trunk of a horizontal well after its stop (Morozov, 2009), as well as in the intervals of opening of the stopped imperfect vertical well (Morozov, 2017).

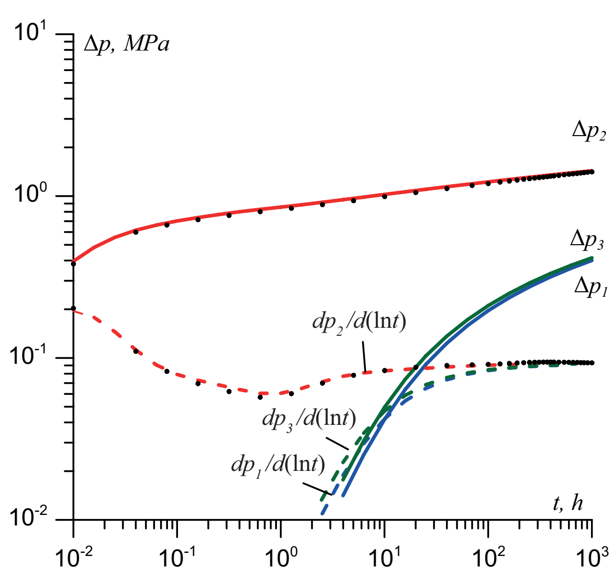
Figure 5a shows the pressure and pressure derivative curves in the HW sections in the case where the second inflow control valve is open. The time delay and the amplitude of the pressure response in the inactive sections of the HW trunk practically coincide. The symbols in Figure 5a shows the results of calculations of the pressure and pressure derivative in a HW with a barrel length of 80 m and a skin factor $S = 1$ obtained in the Saphir package. As in the previous example, a fluid flow occurs through inactive sections of the HW trunk (Figure 5b).

Figure 6a shows the pressure and pressure derivative curves in the sections of the HW in the case where the first and third inflow control valves are open ($p_1 = p_3$). On the graph of the pressure derivative in the active sections of the HW trunk, two sections can be distinguished, characterizing the pseudo-radial flow regime. The first section characterizes the pseudo-radial flow regime to the active sections of the HW trunk prior to their mutual influence, the second section is the pseudo-radial flow regime to the HW at large times.

Comparing the derivatives of pressure in Figure 3a and Figure 6a, it is seen that with the disconnection of the second section of the HW trunk, the time to reach the late radial flow regime changes insignificantly. The fluid flow through the second section, which is located between the active sections of the HW trunk, has an arcuate shape (Figure 6b). The slight asymmetry in the inflow of the liquid in Figure 6b is due to the difference in the skin factor in the trunk sections of the HW.

Conclusions

The paper provides a semi-analytical solution to the problem of non-stationary inflow of liquid to a multi-section horizontal well with controlled selection. The effect of the opening and closing of the inflow control valves on the pressure and pressure derivative curves



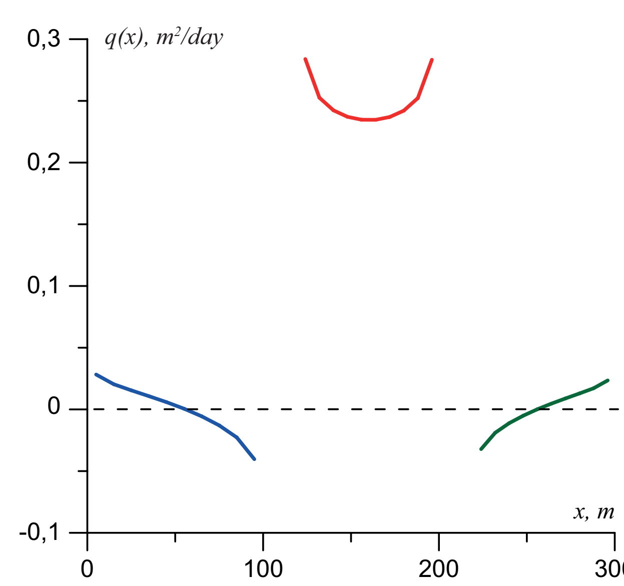


Figure 5. Pressure and pressure derivative curves (a) and distribution of fluid flow along the HW trunk (b), the second valve is open

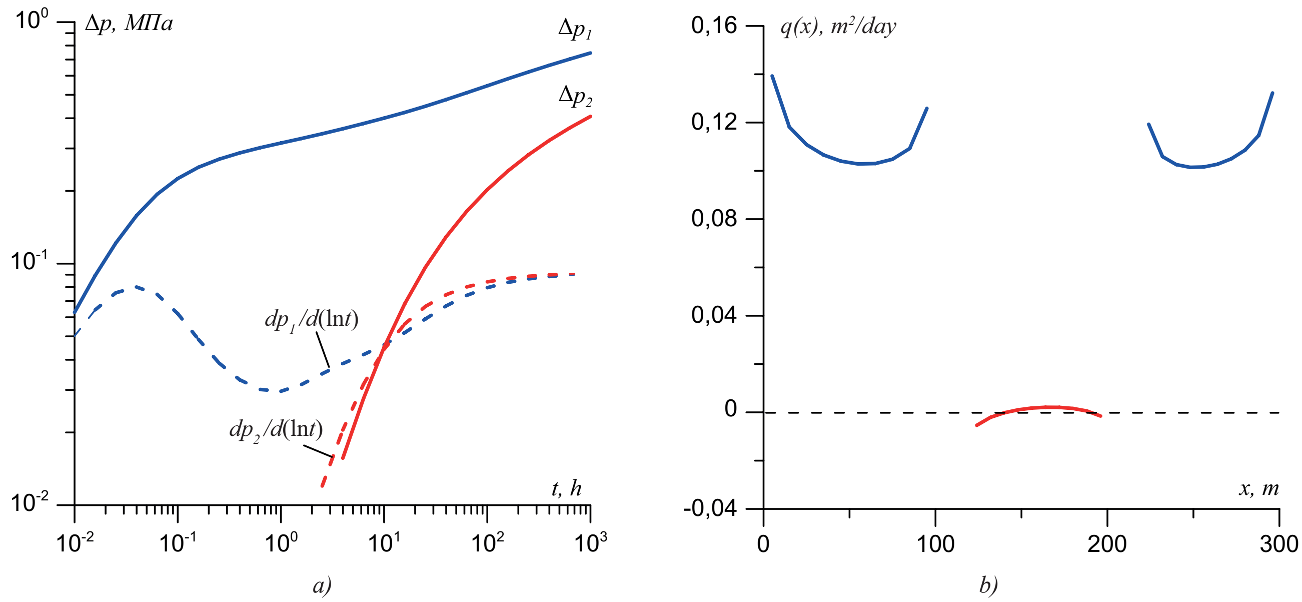


Figure 6. Pressure and pressure derivative curves (a) and distribution of fluid flow along the HW trunk (b), the first and third valves are open

in sections of the HW trunk is analyzed. Calculations showed that through the inactive sections of the HS trunk an "overflow" of the liquid takes place. Therefore, the effect of the "overflow" of the liquid should be taken into account when conducting and interpreting the results of thermohydrodynamic studies of multi-section horizontal wells with controlled selection.

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Substantiation of the hydrodynamic disintegration of hydraulic fluid's mineral component of high-clay sand in precious metals placers

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Abstract. General regularities and theoretical approaches determining hydroimpulsive effects on the mineral component of the hydraulic fluid are analyzed, with reference to the disintegration of high-clay sands of gold-bearing placers. Theoretical conclusions on the hydrodynamic effect on the solid component of the hydraulic fluid give insight into emerging processes in multicomponent media under hydrodynamic influences initiated by various sources of physical and mechanical influence. It is noted that the theoretical justification of the structurally complex hydrodynamic effect on the hydraulic fluid with the formation of phenomena arising from the collision of solid components with each other and obstacles includes the consideration of changes in such force characteristics as speed, pressure, flow power, and also changes in design parameters and characteristics of the environment.

A conceptual approach is given to the theoretical substantiation of the disintegration of the hydraulic fluid's mineral component using the example of the proposed installation. Calculation of economic indicators for the use of a hydrodynamic generator in comparison with processes based on known technologies has shown significant advantages of using the proposed installation, which can increase productivity and quality production indicators.

Keywords: hydraulic fluid, mineral component, disintegration, jet separation, cavitation

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At present, new types of placers are being commissioned in the Far East region, previously not related to industrial facilities for the content of valuable components. A considerable number of placers discovered in the Amur region are characterized by small gold and an increased content of clay fractions. According to the data of geological studies of gold-bearing placers in the Far East of Russia, more than 60% of them are clayey. Analysis of placer fields in the Amur region showed that many of them can be classified as complex for processing because of the significant volume of fine gold (fractions less than 0.5 mm make up more than 90%, and gold sizes less than 0.1 mm – up to 26%). An example is the Kutum field, a sieve analysis of the gold bearing stratum of which showed a 93% of gold content of 0.16-0.63 mm in size (Figure 1) (Khrunina et al., 2011).

The Kutum field is located in the Sutar gold-bearing area, in the zone of the right-bank inflow of the River Sutara. The length of the placer is 4 km; the average width is 62.1 m; the thickness of loose deposits is 5.4 m; peat thickness – 3.1 m; the thickness of the sands is 2.3 m. The composition of the loose sediments: the soil-vegetation layer is 0-0.3 m; Peat with silt – 0,3-1,2 m; quartz-feldspar sand, fine-medium-grained with silt, rare fragments of granites, in the lower layers peat and brown clay interlayers (0.5-1.0 m) – 1.2-3.0 m; quartz-feldspar sand coarse-grained with gravel, rubble and a small amount of pebbles – 3-5 m. The granulometric composition of the loose deposits of the Kutum field is presented in Table 1, the sieve analysis of gold in Table 2. The lower parts of the gold-bearing strata enter the destroyed granites . On the terraces there is more clay fraction.

The high energy intensity of the mining machines and technological equipment used, the poor quality of the disintegration process of high-clay sands of placers, the significant losses of valuable components exceeding 50%, caused not only by deviations in technological regimes from optimal values, but also by imperfect machine designs, reduces the efficiency of processing gold-bearing sands (Mamaev et al., 2015).

One of the fundamental tasks of the destruction

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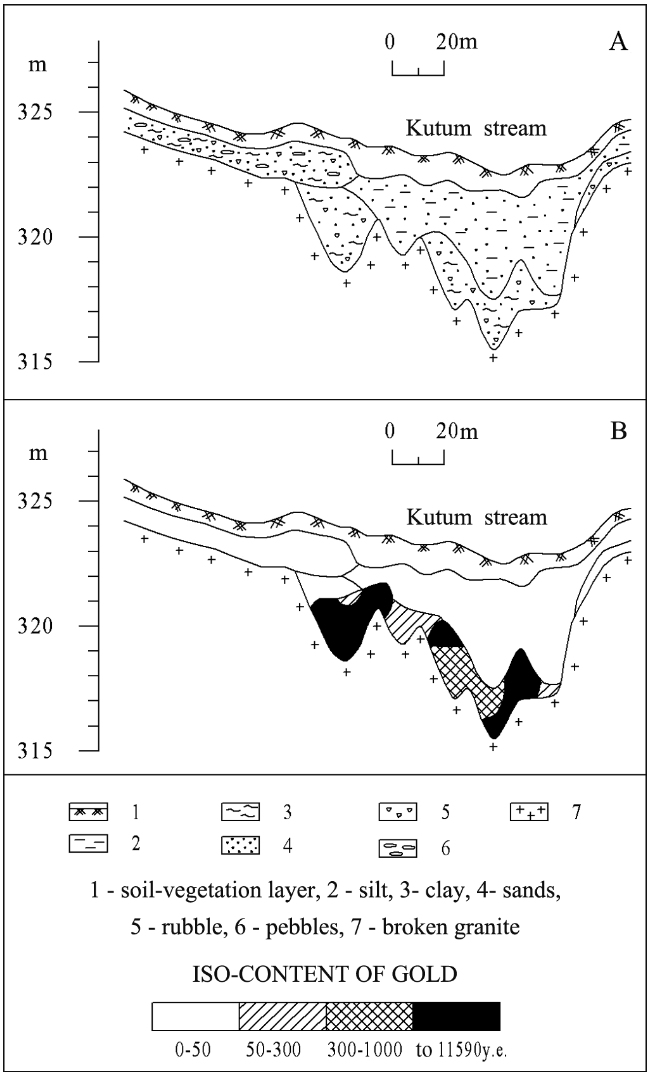

Figure 1. Cross sections of the Kutum placer: A – lithological section; B – section of gold content

Fraction, mm	-2	2-10	10-200	200-300
Composition, %	46,9	43,3	11,3	0,5

Table 1. The granulometric composition of the loose deposits of the Kutum field

Grain-size category, mm	-0,16	0,16-0,63	0,63-2,5
Composition, %	3	93	4

Table 2. Sieve analysis of gold from the Kutum field

processes in liquid media is to elucidate the nature of the appearance and propagation of waves interacting with deformable bodies (Ganiev, Ukrainskiy, 2011; Kulagin, 2000; Rudenko, 1993; Fedotkin, Nemchin, 1984). The processes of energy conversion between vibrational and translational forms of motion can cause both amplification of oscillations and the appearance of unidirectional flows.

Statement of the problem and analysis of approaches to its solution

Understanding the complex mechanisms of wave interaction, the dynamics of their propagation and cavitation can allow controlling these processes. (Khrunina, 2014). Consideration (Kizevalter, 1979) of the equilibrium is given, acting on a particle of forces in the case of gravitational separation of a solid in hydraulic fluid, which is expressed by the dependence:

$$V\rho_{т}g - Vg\left[(1-m)\int_{\rho_{т1}}^{\rho_{т2}}\gamma d\rho_{т} + m\rho_{ср}\right] - VК_{м}\frac{1}{\gamma(\rho_{т})}grad\,\gamma(\rho_{т}) - av = 0, \quad (1)$$

where V – the volume of the particle; $\rho_т$ – the particle density; m – content of the medium (water) per unit volume of suspended matter; g – the acceleration vector of gravity; γ – the density distribution function of particles, $\int_{\rho_{т1}}^{\rho_{т2}}\gamma d\rho_{т}$ – fraction share in the range of density change from $\rho_{т1}$ to $\rho_{т2}$; $\rho_{ср}$ – the average density of the medium; v is the vector of the average particle velocity; $K_м$, a – the coefficients.

Theoretical conclusions on the gravitational separation of solid in hydraulic fluids give general ideas about emerging processes in multicomponent media under hydrodynamic influences initiated by various sources of physical and mechanical influence.

The aim of the research is to develop an approach to the substantiation of the disintegration process of high-clay sand under the conditions of changing the pressure of the flow, with the formation of vortices, shock waves, and dilution of the hydraulic fluid, on the basis of an analysis of the aspects of hydrodynamic phenomena and interactions.

The results of the study and their discussion

To substantiate the disintegration processes of the mineral component of the hydraulic fluid under conditions of resonant acoustic phenomena in the hydro-flow and to determine the technological and design parameters of the systems simulating the cavitation and hydrodynamic effects, it is necessary to identify factors influencing the nature of the process from all the diversity of approaches to the solution of the problem posed. The hydraulic fluid at disintegration is a liquid with solid inclusions. It is known that the strength of a liquid is sharply reduced when it contents solid particles or gas inclusions. Proceeding from the molecular theory, the tensile pressure necessary for the occurrence of ruptures in water at 20°C is 3200 kg/cm^2. However, the phenomenon of cavitation is observed in the liquid long before reaching the value of the tensile force. This indicates that during the cavitation process a rupture of the cavitation pocket occurs in the places of thermal fluctuations of the liquid. The rupture of the liquid occurs at the boundary with the solid surface of the suspended particles. In addition, microcracks of solid suspended particles may initiate the appearance of cavitation effects, as well as a different degree of wetting of the particles may contribute to the formation of cavitational discontinuities (Kruglitskiy, 1971).

To study the process of disintegration by means of cavitation, samples of high-clay sands from one of the sections of the Besheny field of Primorsky Krai were selected. Samples of 150 g were placed in water and were cavitated by IMAHASHI (model USD150B) unit. The disintegration was estimated by the change in the mass of mineral particles separated from the sample. The separated part of the mineral particles separated with water was drained, dried in an oven and after cooling it was weighed on a laboratory electronic scale OHAUS Scout Pro SPU202 (Mettler Toledo, China) with a systematic error of ± 0.001. Based on the results of studies, the dependence of the intensity of cavitation on the mass of the disintegrated clay component of the slurry is established (Figure 2).

The process of disintegration initiated by ultrasonic action and mechanical stirring of smaller samples and the clay component of the hydraulic fluid were also compared. To do this, samples of 35-40 g, with average initial moisture content of 12%, were weighed on laboratory electronic weighbridges OHAUS Scout Pro SPU202 (Mettler Toledo, China) with a systematic error of ± 0.001, then placed in water purified by filtration using the REVERSE OSMOSIS SYSTEM system "ATOLL 560". The time of action on the mineral mixture with pieces of samples was 5, 10 and 15 min. The average value of the specific interfacial surface of the particles (fractions less than 0.5 mm) was determined by the sandy-clay composition of the mineral hydraulic fluid after mechanical and cavitation effects (Figure 3). The dispersion of the fraction less than 0.5 mm was established using a Fourier spectrum in a mineral slurry medium by means of an "Analysette 22 MicroTec Plus" laser diffractive microanalyzer (Fritsch GmbH, Germany) operating on the basis of a converging laser beam and using the physical principle of electromagnetic wave scattering to determine the particle size distribution. The estimation of random errors was performed on the basis of the Student's method with a reliability value of 0.95 and the number of measurements n=5, and the elimination of gross errors in the statistical series by the rule of three sigma.

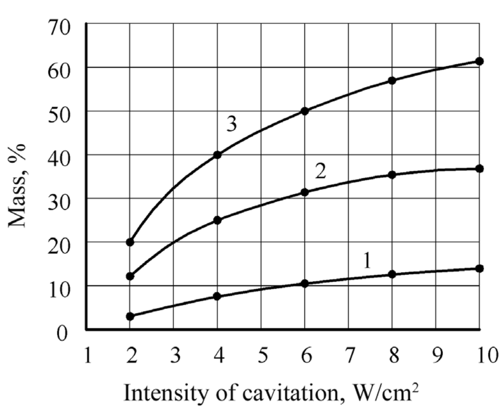

Figure 2. Dependence of the disintegration degree of the sandy-clay component of the mineral hydraulic fluid on the intensity of cavitation, with the time of action (min): 5 (1); 10 (2); 15 (3)

Considering the theoretical plan proposed for the practical use of the installation (Khrunina, 2014), it is possible to distinguish simulated hydrodynamic effects in a number of zones of its working space that are initiated by cavitation, including due to the configuration of the hull that creates changes in the pressure of the hydraulic fluid at the inlet – in the diffuser, which turns into a confuser (Figure 4). Material processing will be carried out under conditions of active hydrodynamic influences by means hydrodynamic generator placed inside coaxially and in series connected stationary cavitation elements. There are no moving parts in the installation. Energy costs go only to the supply of pulp under pressure.

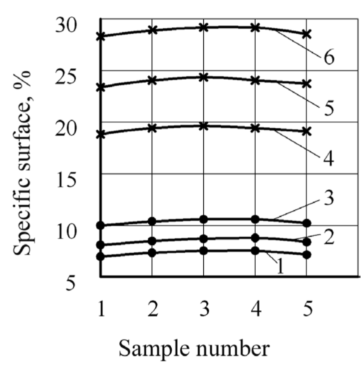

Figure 3. Dependence of the disintegration intensity at 5, 10 and 15 minutes, respectively: 1-3 – with mechanical stirring; 4-6 – with ultrasonic cavitation

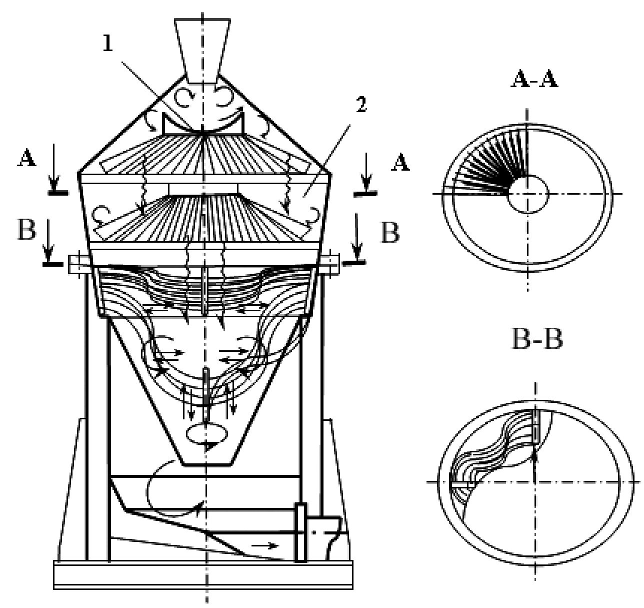

Figure 4. Hydrodynamic generator of jet-acoustic disintegration of the mineral component of the hydraulic fluid

The initial stage of disintegration is carried out by means of a high-speed jet supply through the inlet hole directly to the reflective spherical surface 1 located in the upper part of the housing and mating at the base of its lower part with successively installed cone-shaped cavitational surfaces. A reflective spherical surface 1 with diffuser walls forms a shock wave that transforms into a toroidal cavitation zone with an increase in the shock oscillations and the appearance of fields of primary hydrodynamic and secondary acoustic cavitation in the hydraulic fluid. With a high pressure gradient, the hydraulic fluid successively falls on the tapered cavitational surfaces with slot-like openings and blades. The blades play the role of additional cavitators. The slurry is cavitated and divided into thin streams, passing through the slit-shaped openings. Then the hydraulic fluid enters the zone of the stepped confuser. With the help of packages of movable elastic plate-like cavitation elements made with bends and sagging relative to the fastening, additional jet separation is performed with increasing cavitation-acoustic influence on the mineral component of the hydrosphere and obtaining a given average value of the volumetric power density of the hydrodynamic disturbance to provide a pressure gradient, exceeding the strength limit of microparticles. At the output, it is possible to obtain mineral components of a hydraulic fluid with a particle size within 1-2 μm. The arrangement of the intermediate fastenings of the lower pack of elastic plateau cavitation elements with a significant displacement in the vertical plane provides a significant vortexing both in the flow direction of the hydraulic fluid and perpendicular to it. The frequency range of the radiation obtained during cavitation in the disintegration process can be in the range 0.4-40 kHz (Mamaev, Khrunina, 2008), and the velocity of the jet from the inlet controls the maximum of the sound pressure.

In the pressure zone of the jet of the mineral hydraulic fluid to the enclosing surface 1, without taking into account the recessed jet in the upper region of the expansion-diffuser, the pressure of the jet is determined by the formula (Idelchik, 1975):

$$\mathrm{P} = \frac{\gamma}{g} Qv(1 + cos\beta) = \rho Qv(1 + cos\beta) = \\ = \rho Qv\big(1 + (-0{,}5)\big) = 0{,}5\rho Qv, \quad (4)$$

where γ – the volumetric weight of the liquid; g – acceleration of free fall; Q is the flow rate; v – the velocity of the liquid jet; β – the angle between the tangent to the enclosing surface and the axis of the jet; ρ – the density of the hydraulic fluid.

In the narrowing-confusion zone 2, the loss of pressure is determined by the formula (Idelchik, 1975):

$$h = \zeta_{суж} \frac{v_2^2}{2g}, \quad (5)$$

where the coefficient of contraction resistance is determined by the semiempirical formula:

$$\zeta_{суж} = 0{,}5\left(1 - \frac{S_2}{S_1}\right) = 0{,}5\left(1 - \frac{1}{n}\right), \quad (6)$$

in which $n = S_1/S_2$ is the degree of restriction. Hydrodynamic effects should also be considered in the following zones of the installation, which are below. The intensity of hydrodynamic cavitation, which ensures the destruction of the mineral component of the hydraulic fluid at the final stage, will be proportional to the change in the speed of the water flow (Promtov, 2001)

$$\mathrm{I} = (V - V_{кр})^n, \quad (7)$$

where V – the initial flow velocity at the entrance to the confuser; V_{cr} – the critical velocity corresponding to the instant of the beginning of cavitation destruction; n – the exponent, determined from the experimental data.

An analysis of the phenomena occurring in the conditions under consideration requires further development. In addition, the main factor of interest to us is the result of the destruction, disintegration of the solid mineral component of the slurry. The investigated process of vortex and pulsed hydrodynamic action on the solid component includes elastoplastic deformation and fracture with the formation of new surfaces of small particles S, which will depend on the intensity of hydrodynamic cavitation

$$S = f(\mathrm{I}) = f\,[(V - V_{кр})^n]. \quad (8)$$

The efficiency of disintegration depends on the physico-mechanical features of high-silt sands, including the effect of the medium, and various types of hydrodynamic effects. In the hydrodynamic generator, the main forces of action are the hydrodynamic forces of the flow, as well as the mechanical forces of interaction of the particles with each other, with the walls and other elements of the generator. One of the factors that should be taken into account in justifying disintegration at the microlevel is the study of the effect of water saturation on high-clay sands of placers. The application of new approaches to the assessment of the influence of water saturation on the disintegration processes of high-clay sands and the expansion of the investigation objects, with a more detailed study of the effect of water saturation on the elastic characteristics of clay sands in placers, broadens the possibilities for the development of theoretical studies of hydrodynamic phenomena.

The economic efficiency is given of the processing high-clay sand (clay content above 30%), with an increased content of small and fine particles of valuable components, based on the use of a developed cavitation plant (Khrunina, 2014), compared to two basic options based on the physico-chemical method of selective exposure to polyelectrolyte complexes (Myazin, 1996) and using the widely applied PGSh-50 complex. The economic advantage of disintegration through cavitation initiation in comparison with the physicochemical method of selective action of polyelectrolyte complexes, according to the methodology (Bogatin, 1999), is the reduction of the transferred costs for the new technology. Calculations have shown that the use of two cavitation generators in a standard enrichment scheme, including a deep filling gateway, a washout and classification system, and thin-layer screw sluices, can reduce the present costs by 38%.

Comparison of the disintegration process through the proposed installation with the process based on the PGSh-50 complex according to the methodology (Bogatin, 1999) was carried out on the calculation basis of the resulted effect, since these processes differ in the volume of production and in the quality of the products (i.e., with functional solutions tasks). Compared with the disintegration process based on the PGS-50 complex, a system with the use of hydrodynamic cavitators is most preferable, since its reduced effect is 4 times higher, i.e. productivity and quality indicators of production significantly exceed not only by economic, but also by technological indicators.

Conclusion

More than 350 fields and occurrences of gold and gold with silver have been taken into account on the territory of the Khabarovsk Territory. Of the 180 gold fields, most of which are placers, including with increased clay content – up to 80% and more, a significant part of them is not ready for development due to the lack of environmentally and technologically efficient technologies. This includes the Amur Region, in which about 630 placers are also found with considerable clay content and a high content of fractions with small and fine gold particles and other valuable components. The use of the proposed installation based on hydrodynamic cavitation will solve the problem posed. The theoretical justification for a structurally complex hydrodynamic effect on a hydraulic fluid includes accounting for changes in such power characteristics as speed, pressure, flow power, and also changes in the design parameters and characteristics of the medium. The development of studies of hydrodynamic impact on multicomponent media of hydraulic mixtures will provide information that will ensure the implementation of technology for the disintegration of high-silt sands of precious metals with a number of significant advantages, including ensuring low energy costs. This will provide new knowledge about the processes and phenomena under study and solve the rather acute problem of complex processing of mineral raw materials by effective and environmentally safe physico-mechanical methods.

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