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Article / Статья

Systematic Analysis of the Results of Studying a Technogenically Formed Spatially Heterogeneous Drainage Zone of Horizontal Wells

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Системный анализ результатов исследования техногенно сформированной пространственно неоднородной зоны дренирования горизонтальных скважин

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Keywords:
heterogeneous zone drainage of horizontal wells, technogenically formed cracks, tracer studies, low filtration resistance channel, model of the hydraulic system of productive formations, disjunctive faults, flexural-fractural faults.

In this article, using a system analysis of the results of studying a technogenically formed spatially heterogeneous drainage zone of horizontal wells, its geological and physical features that determine design decisions and operational characteristics of wells are studied.
A spatially heterogeneous zone arises as a result of the use of a system for maintaining reservoir pressure during waterflooding as a method of increasing oil recovery from fields.
The use of a systems approach and a set of studies, including geophysical and hydrodynamic methods, modeling and numerical calculations, allowed us to conclude that during intensive development of a pore reservoir, fluid filtration is significantly determined by the formed technogenic fracture component and is characterized by nonlinear effects. The pore type of the reservoir changes and a dual environment is formed in the deposit.
The use of a system approach is justified by the fact that instead of transforming the well arrangement system, superconductivity zones caused by disjunctive faults in the oil field area should be eliminated. The technogenically formed drainage zone of horizontal wells should be taken into account when developing design solutions at the last stage of exploitation of the productive formation.
The results of this research article can be used to improve the efficiency of oil production by increasing the profitable period of operation of horizontal wells in terrigenous reservoirs, in which zones of superconductivity of the interwell space are formed.

Ключевые слова:
пространственно неоднородная зона дренирования горизонтальных скважин, техногенные трещины, трассерные исследования, канал низкого фильтрационного сопротивления, модель гидросистемы продуктивных пластов, дизъюнктивные нарушения, флексурно-разрывные нарушения.

С применением системного анализа результатов исследования техногенно сформированной пространственно неоднородной зоны дренирования горизонтальных скважин изучены ее геолого-физические особенности, определяющие проектные решения и эксплуатационные характеристики скважин.
Пространственно неоднородная зона возникает в результате применения заводнения как метода повышения нефтеотдачи месторождений.
Применение системного подхода и комплекса исследований, включающих геофизические и гидродинамические методы, моделирование и численные расчеты, позволило сделать вывод, что при интенсивной разработке порового коллектора фильтрация флюидов существенно определяется формируемой техногенной трещинной составляющей и характеризуется нелинейными эффектами. Происходит изменение порового типа коллектора, и в залежи формируется двойная среда.
Использованием системного подхода обосновано тем, что вместо трансформации системы расположения скважин следует ликвидировать зоны сверхпроводимости, вызванные дизъюнктивными нарушениями в области нефтяного месторождения. Техногенно сформированную зону дренирования горизонтальных скважин следует учитывать при разработке проектных решений на последней стадии эксплуатации продуктивного пласта.
Результаты исследований данной статьи могут быть использованы для повышения эффективности добычи нефти за счет увеличения рентабельного периода эксплуатации горизонтальных скважин в терригенных коллекторах, в которых формируются зоны сверхпроводимости межскважинного пространства.

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Introduction

The duration of the life cycle and the slow dynamics of field development processes and the irreversible technogenical impacts on the geological environment determine the importance of using systems analysis while making decisions on applied problems of exploitating and monitoring hydrocarbon deposit development. The achievements of the RAS Academician A.E. Kontorovich recognized by the scientific community have proven the effectiveness of using a systems approach that consistently covers the development of fundamental Earth sciences to the use of the obtained results to solve specific problems within the framework of applied research into the process of developing and implementing technologies. This is confirmed by the results of research by followers and students of the scientific school of A.E. Kontorovich [1–5] in solving problems of developing oil and gas reserves in Western Siberia [3, 5] and developing, adapting and implementing new technologies for the extraction of hard-to-recover hydrocarbon reserves [4, 6, 7]. It is known that the trend of oil production in Western Siberia for the next decades will be determined by the efficient development of hard-to-recover reserves in the Upper Jurassic and Middle Jurassic complexes which share exceeds 30 % in the total structure of oil and gas province reserves [4].

In conditions of productive low-permeability formations characterized by the absent frontal component of the process of uniform displacing oil by water, the basis for oil recovery is the capillary recharge of a branched crack system.

Of scientific and practical interest there is the studying the geometry of cracks technogenically formed during the operation of injection and production wells, the patterns of their spatial distribution as well as the relationship between crack formation and technological indicators of oil field development. An assessment of the reasons determining the spatial location of technogenical cracks, and the geological and technological conditions determining the direction of their priority development will make it possible to organize formation pressure maintenance (FPM) systems. Taking into account the formed spatially heterogeneous drainage zone creates a favorable basis for increasing the profitable period of well operation and the oil recovery factor.

Technogenical drainage zone of the productive formation

The design and technological documents for field development [8] substantiate the use of dense well grids and selective flooding. At the first stage, productive formations and areas with the best reservoir properties were brought into development.

A focal-selective flooding system with a grid density of 16 ha/well was formed in the deposits of the Tyumen suite. The analysing the development results for the same period of time revealed a significant difference in the efficiency of oil reserves development at the fields (Fig. 1).

While interpreting the results of 250 hydrodynamic studies (HDS) using fields 2 and 3, reservoirs with a dual environment were identified that were not established at the beginning of development [8]. The fluid filtration process is described by the Barenblatt-Warren-Root model (see Fig. 1). The presence of dual permeability is confirmed by the results of studying the filtration-capacitive core properties. At fields 2 and 3, anomalous values of core sample permeability are observed (~3–5 % of determinations) which indicates the presence of a fracture component.

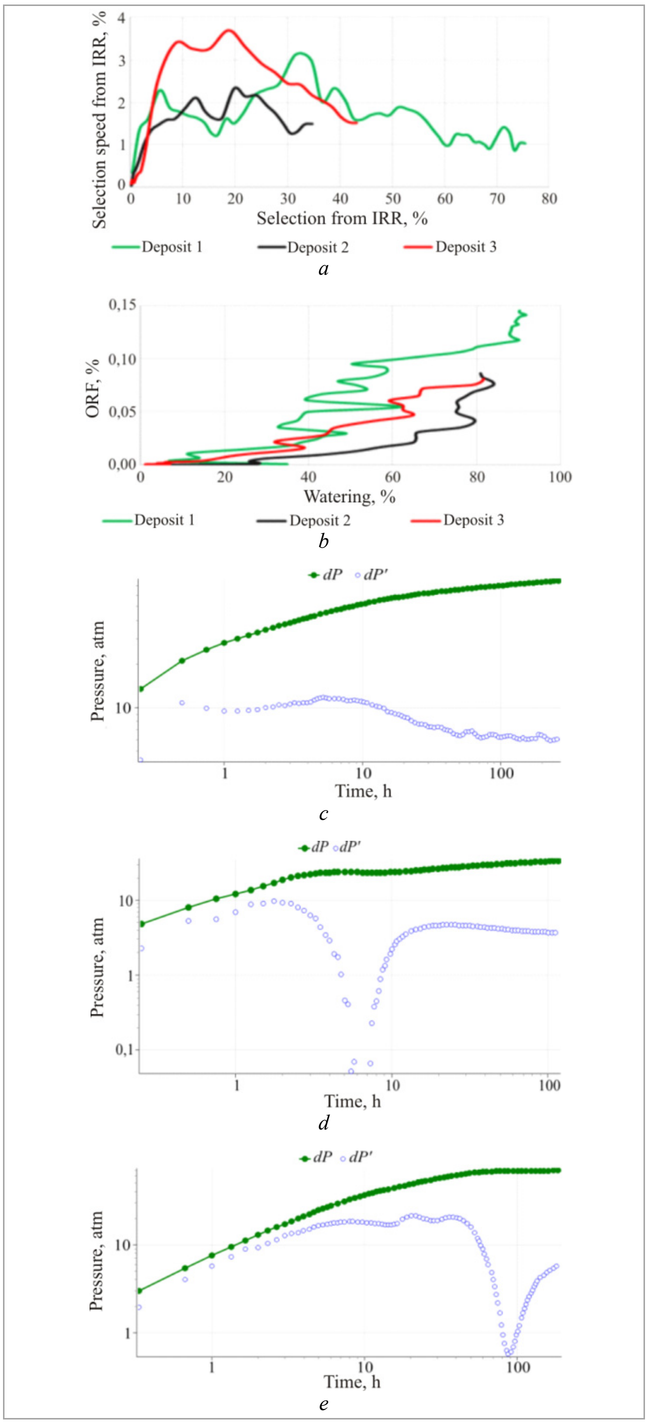

Fig. 1. Development indicators of the study objects: *a*, *b* – development indicators; *c* – diagnostic graph of the pressure build-up characteristic of the first field wells; *d* – diagnostic graph of the pressure build-up reservoir characteristic with a dual environment in the second field wells; *e* – diagnostic graph of the pressure build-up reservoir characteristic with a dual environment in the third field wells

It has been established that the presence of dual-medium reservoirs at fields 2 and 3 has a negative impact on the efficiency of flooding technology: low value of the current oil recovery factor (less than 10 %); high water cut of the extracted product (more than 80 %).

It is known that the interpretation of tracer studies results establishes the presence or absence of a hydrodynamic connection between injection and production wells, reveals the presence of powerful fracture systems of low filtration resistance (LFR) in the reservoir which lead to unproductive filtration of injected water [9, 10].

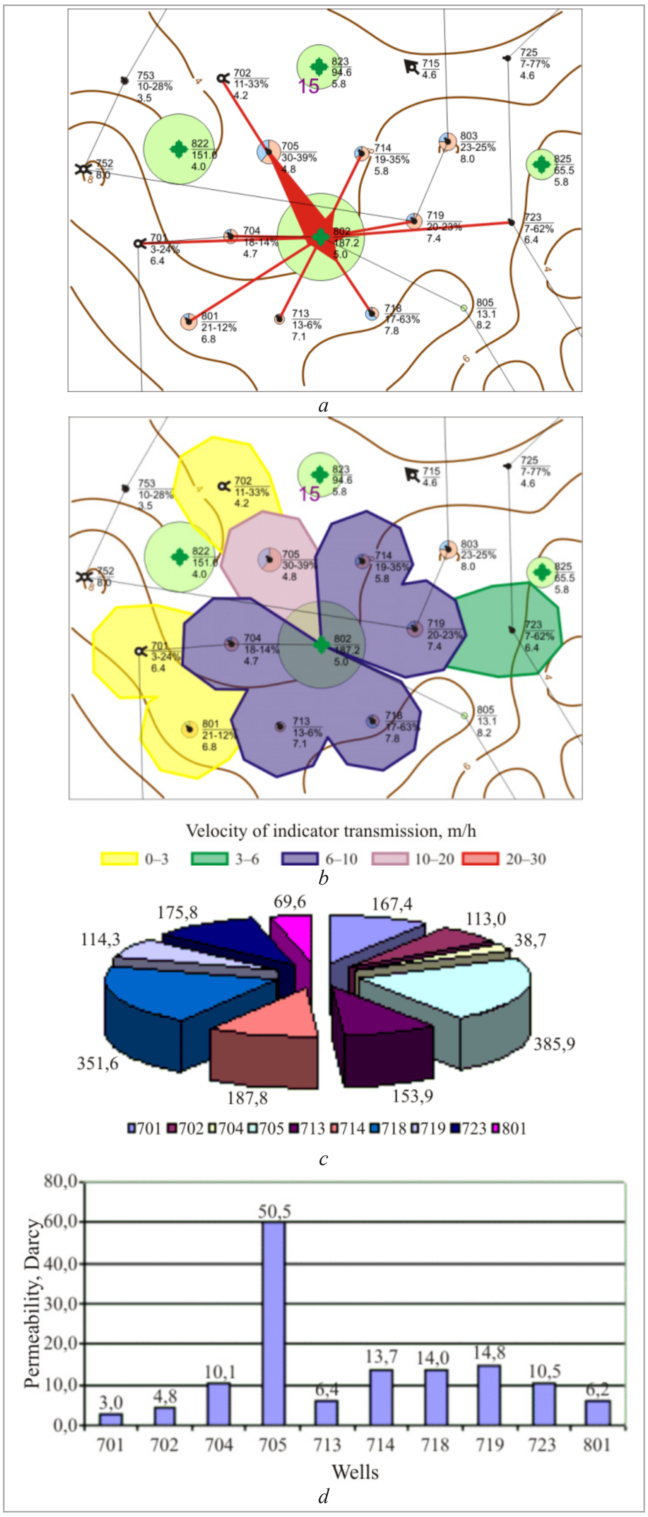

Fig. 2. Interpretation of tracer study results: *a* – rose diagram of reduced indicator movement velocities from well No. 802; *b* – after indicator movement velocities from well No. 802; *c* – distribution of LFR channel volumes to production wells from well No. 802; *d* – permeability of LFR channels to production wells from well No. 802

A comprehensive analysing the results of indicator studies, geological, geophysical and production data on wells of field X made it possible to identify the distribution of injected water by the area and section of productive formations and the coverage by displacement (Fig. 2).

It was revealed that the reason for the high water cut of wells within the studied area in the area of injection well 802 is the presence of LFR channels which length is commensurate with the interwell deposit space. In our opinion, the researchers who conducted and interpreted the results of indicator studies using the SevKavNIPIneft methodological manual, the identified LFR channels can be very small in cross-section and do not have a significant effect on the displacement process.

In this regard, it is proposed to conduct a system analysing the technological indicators of the injection and production wells operation (maintenance of reservoir pressure is ensured by flooding the deposit) [11]. Mathematical processing data on the dynamics of injectivity and bottomhole pressure is carried out taking into account the hydraulic interaction with a group of adjacent production wells and the assumption that in injection wells where an increase in injectivity is accompanied by a drop in bottomhole pressure, destabilization of reservoir pressure occurs due to the forming technological long cracks directed to the selection zone.

Figure 3 shows the results cconnected with the dynamics of the injectivity of an injection well in the form of a tabulated function $R(t)$, wellhead pressure $p_y(t)$ and fluid flow rates of production wells in the form of a tabulated dependence $Q(t)$.

The distance cutoff principle or the triangulation scheme based on the Delaunay method is used to determine potential interaction lines between the injection well with dynamics – $R_0(t)$, $P_0(t)$ and N production wells with dynamics $Q_i(t)$.

The dynamics of the bottomhole pressure in the reference injection well $p_0(t)$ is studied based on the telemetry of the dynamics of its injectivity $R_0(t)$ and the dynamics of the flow rates $Q_i(t)$ of the wells adjacent to it. The desired function $p_0(t)$ is calculated based on the desired values of permeability (or piezoconductivity) along the selected interaction lines so that the sum of the deviation squares at the points of actual measuring of the bottomhole pressure $P_0(t)$ is reduced to a minimum

$$\Sigma\left[p_0(t)-P_0(t)\right]^2 \rightarrow \min, \qquad (1)$$

where the summation is performed over all available measurements of the bottomhole pressure in the reference well.

It is known that

$$p_0(t)=P_0(t_0)+\mu_0\frac{R_0(t)-R_0(t_0)}{4\pi k_0 h_0}Ei\left(\frac{\mu_{0(m\beta_1+\beta_p)}r_c^2}{4k_0(t-t_0)}\right)+ +\sum_{i=1}^{N}\mu\frac{Q_i(t)-Q_i(t_0)_i}{4\pi k_i h_i}Ei\left(\frac{\mu_{(m\beta_1+\beta_p)}r_i^2}{4k_i(t-t_0)}\right), \qquad (2)$$

will be correct only for $t > t_0$. The ranges of measurements for all wells are different (since the wells are not started simultaneously), it is necessary that in the absence of measurements and $t < t_0$, $R_0(t) = 0$, $Q_i(t) = 0$, $P_0(t) = P_{pl}$, where P_{pl} is the initial reservoir pressure.

In (2) there are $N+1$ unknowns – k_0 and k_i for $i \in [1 \ldots N]$, and their definition relates to the problem of nonlinear programming for finding the minimum of the function with respect to unknown permeabilities along the lines of well interaction

$$\Omega(k_0,k_1,\ldots,k_i,\ldots,k_N)= =\sum_{j=1}^{M}\left[p_0(t_j)-P_0(r_j)\right]^2 \rightarrow \min, \qquad (3)$$

where j is the number of the bottomhole pressure measurement in the reference well; t_j is the time corresponding to the jth measurement; M is the number of bottomhole pressure measurements in the reference injection well. Substituting (2) into (3) we obtain that

$$\Omega\left(k_0,k_1,\ldots,k_i,\ldots,k_N\right)= \\ =\sum_{j=1}^{M}\left[\begin{array}{l} P_0\left(t_0\right)+\mu_0\dfrac{R_0\left(t\right)-R_0\left(t_0\right)}{4\pi k_0 h_0}Ei\left(\dfrac{\mu_{0\left(m\beta_l+\beta_p\right)r_c^2}}{4k_0\left(t-t_0\right)}\right)+ \\ +\sum_{i=1}^{N}\mu\dfrac{Q_i\left(t\right)-Q_i\left(t_0\right)_i}{4\pi k_i h_i}Ei\left(\dfrac{\mu_{\left(m\beta_l+\beta_p\right)r_i^2}}{4k_i\left(t-t_0\right)}\right)-P_0\left(r_j\right)\end{array}\right]^2\to \quad (4) \\ \to \min,$$

where E_i is an integral-exponential function; k_i is the permeability along the line of interaction of the reference injection well and the adjacent well i; hi is the average effective thickness of the formation in the zone between the wells, determined based on the results of geophysical studies; μ is some averaged dynamic viscosity of the filtered oil and water under reservoir conditions; β_l is the averaged coefficient of liquid compressibility; β_p is the coefficient of rock compressibility; m is the coefficient of open porosity; r_i is the distance between the bottomholes of the reference well and those adjacent to it; k_0, h_0 are the permeability and thickness of the formation in the immediate vicinity of the bottomhole of the reference injection well; μ_0 is the dynamic viscosity of the injected water under reservoir conditions in the reference injection well; r_c is the reduced radius of the reference well.

The method has a limitation related to the observation time, or more precisely, to the difference in the time of change of the well mode and the observation time. At low values of piezoconductivity and long-term observation, the passage of pressure pulses will not be detected when calculating the dynamics of bottomhole pressure. There will be unacceptably large errors at intervals of pressure spread less than 0.2 MPa. It is proposed to periodically change the value of the injectivity of injection wells within 20–40 %.

A number of authors [12, 13] describe the formation of man-made cracks based on the hypothesis of uniform distribution of the strength properties of the reservoir and skeletal stresses, based on the conditions of the reservoir location. In this case, the direction of the crack is determined by the largest gradient of reservoir pressure exceeding the critical fracture gradient (Fig. 4).

The shape of the crack will most likely correspond to the image in Fig. 4. Note that the pressure distribution inside the crack will be uneven due to the unpredictability of the filtration conditions of the fluid during crack formation. As can be seen from the diagrams in Fig. 4, it is assumed that cracks can simultaneously propagate from the center of the cell to the periphery (diagrams 5–15). Two options are investigated in the simulation: *1* – the rupture occurs in all directions where these conditions are met; *2* – the rupture occurs in the direction of the maximum of all pressure gradients corresponding to these conditions.

During the system analysis of the results of the study of the new hydrodynamic simulator “Nemesis 2.0”, which allows taking into account highly detailed non-stationary spatial filtration of multiphase media in fractured-pore reservoirs with pronounced geological heterogeneity and nonlinear interphase interactions [13], it was established that cracks are formed in the injection zones with their propagation into the extraction area which, in turn, contributes to the rapid flooding of production wells.

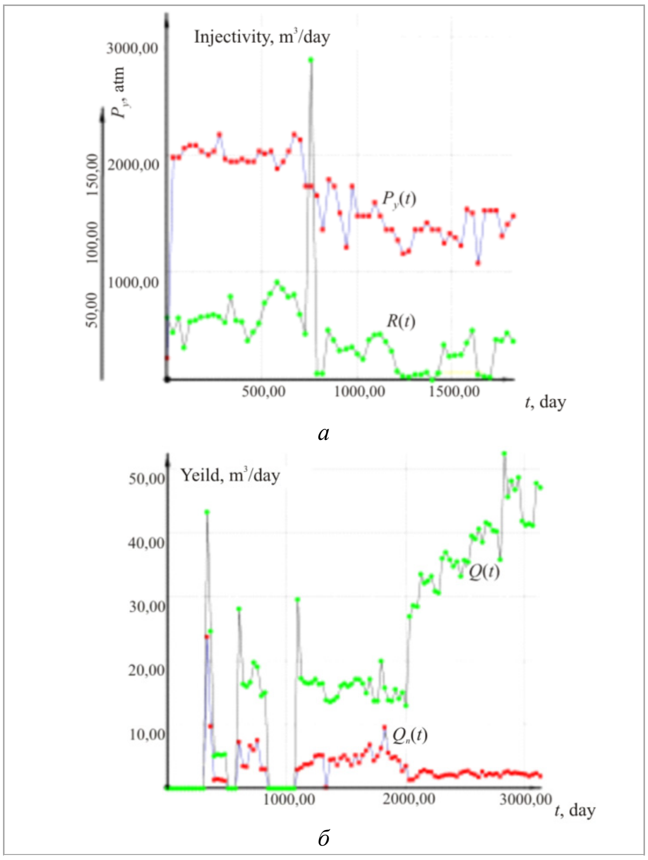

Fig. 3. Examples of initial data for operating modes of injection and production wells at the Van-Eganskoye field: *a* – dynamics of wellhead pressure and injectivity of injection well 306; *b* – dynamics of liquid and oil flow rates of well 1748

Figure 5 shows the dynamics of gradual fracture development in the zone of injection well influence (WIZ) on the formation. According to the accepted hypothesis, the development of the fracture system in the WIZ of injection wells, as well as between wells, depends on the conductivity of the fractures and the fracture gradient. The greater the fracture permeability and the higher the fracture gradient, the larger the formed cracks.

And since the pressure in the WIZ under conditions of small values of the fracture gradient and low fracture permeability is distributed almost uniformly, a network of small fractures in relatively small sizes is created near the injection wells.

The results of computational experiments on the model of the hydraulic system of the productive formation are presented in Table 1.

Even if the balance of selection and injection is maintained, cracks inevitably appear in the bottomhole zones of injection wells. However, with the timely launch of such injection wells, this does not lead to a breakthrough of water into the producing ones. According to the results of the computational experiment, it was found that low reservoir pressure zones are formed at a distance of less than 300–350 m from the bottom of the injection well which is the condition for the development of cracks while starting injection wells. Therefore, it is necessary to adjust the flooding technology in such a way as to ensure water injection along the network of cracks that are formed without getting into the bottom of the production wells which are located at the end of the cracks of the well network. This will lead to a multiple increase in the period of field profitable operation (Fig. 6).

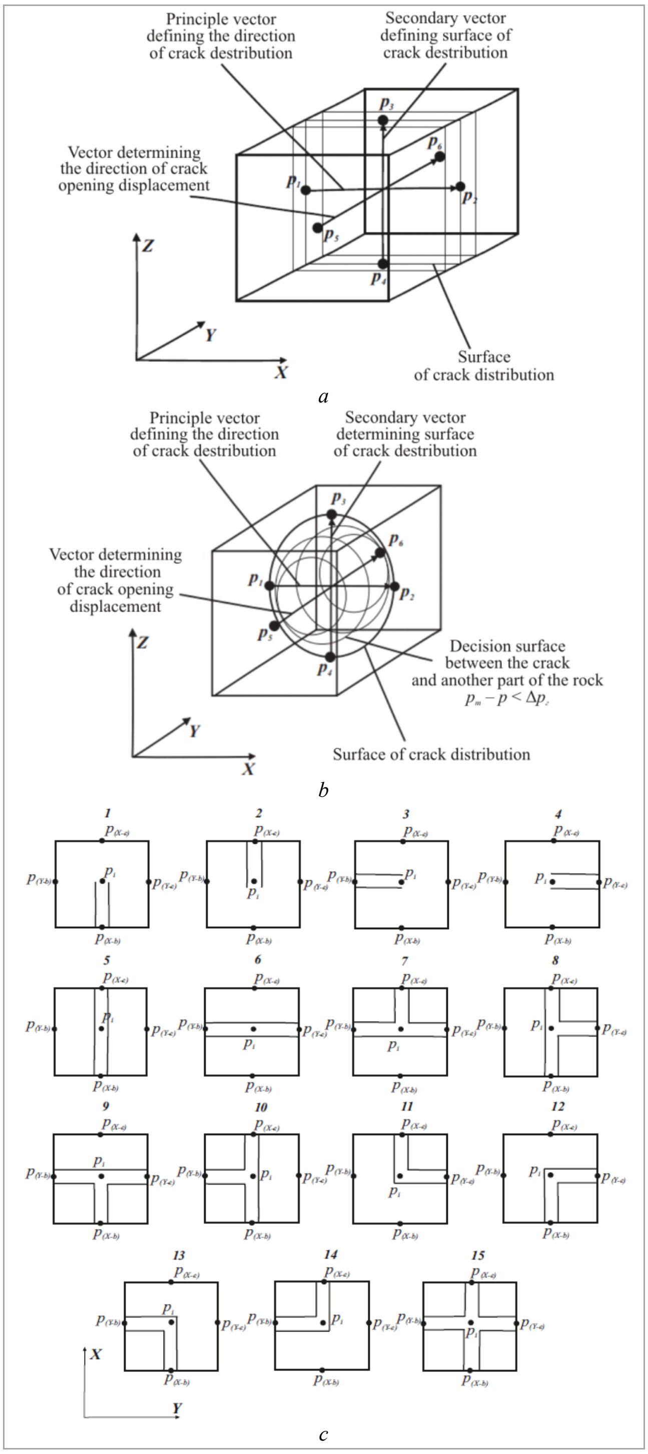

Fig. 4. The process of formated technogenical cracks: *a* – hypothesis of formed technogenically disturbance in the formation element; *b* – crack shape close to natural; *c* – possible combinations of semi-cracks in the cell

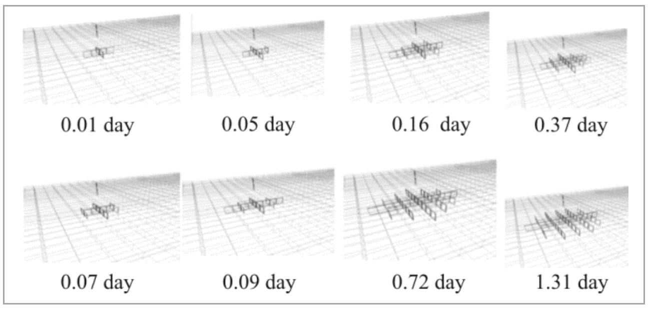

Fig. 5. Dynamics of crack propagation from the injection well

Next, we will consider a methodical approach to designing the development (Fig. 7), based on the using network of technogenically channels as an element of an organized system using the example of the US1 object. As usual, the initial three-dimensional geological model describing the productive formation as a pore-type reservoir with ultra-low permeability was adopted as the basis for constructing the hydrodynamic model. The fracture component is introduced into the model already at the stage of creating and adapting the hydrodynamic model to the development history.

In this case, data from the designs of completed hydraulic fracturing, acoustic studies as well as the results of interpreting hydrodynamic and tracer studies are used.

However, even ideal adaptation of the model and restoration of the fracture component for a certain date do not solve the problem of reproducing the dynamic transformation of the reservoir in the form of the growth and opening of hydraulic fracturing cracks when the reservoir pressure field changes. For this purpose the dependence (Fig. 8) of permeability change on reservoir pressure established as a result of calculation experiments was set in the model, simulating the known results of reservoir transformation in the process of creating bottomhole pressures exceeding the fracture pressure of the rock.

The preferential direction of developing technogenic fracturing determining the movement of reservoir fluid flows was set by the anisotropy parameter for permeability in coordinates (X, Y) and local grid refinement in the areas of injection wells. The grid refinement parameters were selected depending on the geological structure of the object, the time of calculations, etc. For the studied object in the areas of injection wells a refinement of 10 times was adopted.

The approaches used made it possible to create a hydrodynamic model that not only reproduced the fracture system for a certain date, but also incorporated a mechanism simulating the results of the development of the technogenic fracturing system with a change in the dynamics of reservoir pressures in the areas of production wells. The reliability of the reproducing the results of technogenic reservoir transformation, in addition to the adaptation of the hydrodynamic model to the development history, should be confirmed by the results of special hydrodynamic studies that allow us to determine the parameters of hydraulic fractures in injection wells.

The key feature and difference from the approaches to modeling low-permeability objects that are standardly used in practice is the geological and industrial justification of the parameters and the assignment of a new element in the hydrodynamic model – a dynamic system of technogenic transformations of the reservoir.

Multivariate calculations were performed on this hydrodynamic model which made it possible to estimate the technological indicators with a greater degree of reliability and choose the best option for developing the studied deposit.

Based on the results of the technical and economic assessment, the following was proposed:

- adjustment of the injection well operating mode;
- increase in the length of horizontal wellbores;
- increase in the number of hydraulic fracturing stages;
- convergence of injection and extraction zones;
- organization of a row development system.

According to the proposed best option, the increase in cumulative oil production will amount to more than 1.5 million tons or 17 %. The results of practical testing of the method allowed us to conclude that the scope of its application should be expanded.

Table 1

Results of computational experiments on the model of the hydraulic productive formation system

№ п/п	Period of time	Elements of studied displacement process by water	Rusult
1	1–1.5 years	Exploitation wells on the distance less then 800 m from IW (layer thickness is less than 20m)	On the distance less than 300–350 m the zone of low layer pressure is formed
2	Next 1–1.5 years	IW drive	1 – existence of cracks after IW drive on the distance of 200 m during 10–100 days; 2 – expanding of cracks on the direction of low pressure zones in 200–300 days after IW drive; 3 –crack connection from IW and PE after 350–500 days

It is proposed to adjust the flooding technology.

1. Those production wells that are at the ends of the formed fracture network should be converted to injection. Moreover, the closer the well is to the fracture, the earlier it should be converted.

2. To ensure the intensity of displacement, it is proposed to drill new or lateral wells with a horizontal end which feed contours will be effectively supported by the formed fracture network.

3. It is proposed to use the technology of periodic injection with cycles from 1 to 2 years

Note: PW – production well; IW – injection well.

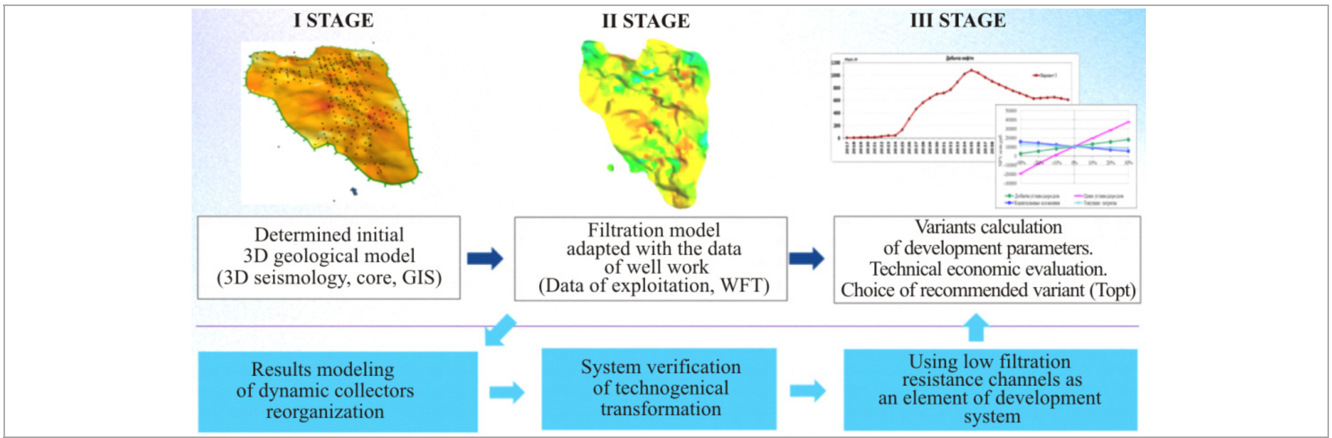

Fig. 6. Schematic diagram of the design of the development using dynamic transformation of a low-permeability reservoir

Disjunctive faults in oil fields

However, the effective application of the proposed methodological approach is complicated (in comparison with the model) by the more significant heterogeneity of hydrocarbon deposits and the existing disjunctive faults of various ranks in oil fields. The features of their filtration structure affect the development process using flooding [14].

Approaches to the studying complex development objects are non-standard and multi-variant. Among other natural factors that complicate the modeling and development of such objects, the following stand out:

– low values of matrix permeability coefficients;
– the existing network of fracture systems;
– very high filtration heterogeneity;
– complex geometry of reservoir systems.

The history of the forming such productive objects does not exclude the presence of combining the above factors which may be a consequence of pronounced fault tectonics. A distinctive feature of such objects is the anomalous filtration-capacitive properties of fractured-porous reservoirs with the so-called «fast» or conductive and «feeding» low-permeability blocks.

A feature of such deposits is that all of the listed complicating factors negatively affect the efficiency of their development to one degree or another.

Typically, fractured reservoirs are modeled by representing them as a continuous medium model, with various versions of using "double" porosity [15]. But such approaches are implemented mainly for designing long-term development forecasts [16]. Since the role of the "fast" medium increases significantly in fractured reservoirs, local problems of detailed development analysis or planning targeted GTM are not solved on such models.

In addition, such objects are poorly determined by standard methods [17], they are not interpreted by GIS methods, are not characterized unambiguously by core and are beyond the resolution of seismic exploration. And if, in the overall picture adopted in single-phase filtration models, the role of such local tasks is not noticeable at the early stages of development, then at the following stages it increases many times over. This leads to dagger breakthroughs of the displacing agent, a sharp increase in its share in the extracted products and, as a consequence, well shutdown.

In these cases, the urgent task is to identify such local objects in a complexly constructed deposit. Most likely, this will be some geological body, no larger in size than a cell of the hydrodynamic model and possessing either high or low values in relation to the environment and introducing significant changes in the direction of filtration flows [18]. The results of the indicator and aerospace studies [10] have established a close relationship between the predominant distribution of the tracer in the formation and the direction of the liniaments which are indicators of flexural-fracture or dynamo-stressed zones of the sedimentary cover. Figure shows disjunctive faults in the area of the N field. It was revealed that the isolines of water in the formation are predominantly parallel or perpendicular to flexural faults and dynamo-stressed zones. By combining the map of accumulated oil production with the map of flexural-fracture faults and dynamo-stressed zones, it was revealed that accumulated oil production is mainly located in faults and in the zones of the most developed reservoir.

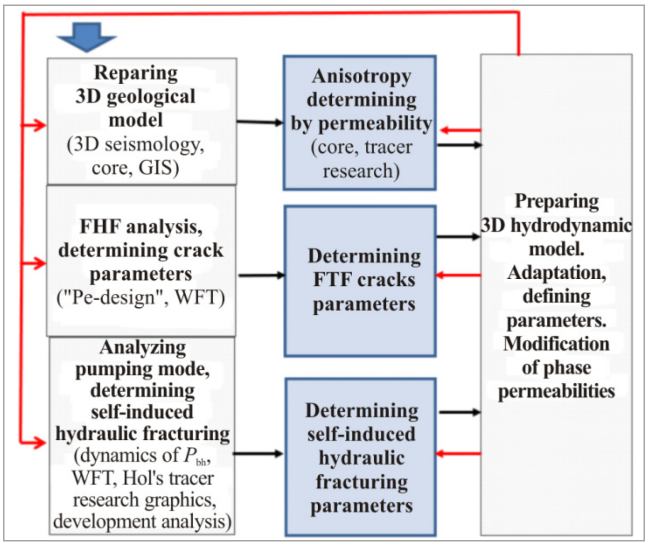

Fig. 7. Block diagram of the methodological approach to justifying the adjusting the development system of a low-permeability terrigenous reservoir in connection with its man-made change

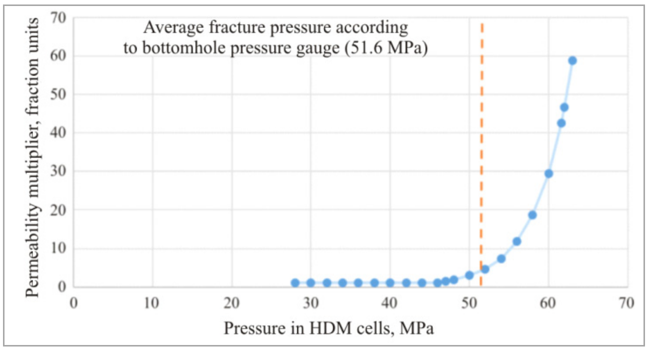

Fig. 8. Permeability multiplier versus pressure in a hydrodynamic model cell used to simulate the effect of dynamic reservoir transformation

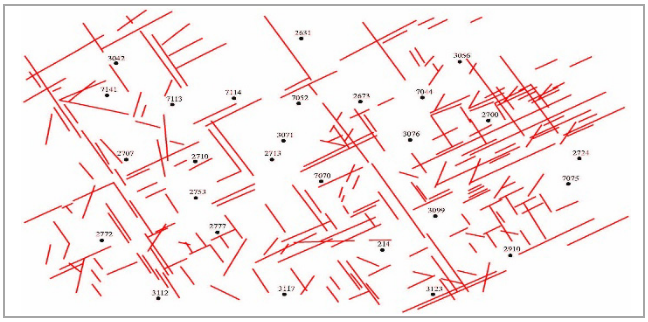

Fig. 9. Flexural faults and dynamo-stress zones in the area of the N deposit

Wells with their bottomholes in faults are the most productive: additional oil inflow is carried out from the reservoir matrix through the LFR channels. When the reservoir pressure maintenance system is launched, premature flooding of the most wells in the facility begin which affects the reduction of the current and final coverage factors by flooding and oil recovery as well as the energetics of the reservoir operation [19–25]. In the work [21] the filtration process in an element of a five-point system in the presence of a LFR channel system connecting the injection and production wells was studied. The conditions under which the channels are located in a horizontal plane were established. If they are not met, the LFR channels are located in a vertical plane. In the work [22] it was established that the pressure gradient has virtually no effect on the size of the two-phase filtration zone and on the proportion of water at an arbitrary point in the formation; changes in the coefficient of water saturation and compressibility of the reservoir have a significant effect. If the repression exceeds the strength limit of the rock with a constant injectivity of the injection well, then man-made cracks are formed. The developed technique makes it possible to establish the filtration boundary of a specific production well by the region of increase in the water cut coefficient of well production. However, the application of the obtained results [21, 22] can be complicated by the following. During the development of an oil field in a complex reservoir, crossflows occur between interlayers, the nature of fluid movement in the areas of production wells changes, and filtration flows are transformed. Part of the liquid injected into the LFR channel, when water moves from the injection well to the production wells, flows into the zone with low filtration parameters (matrix) surrounding the channel. While conducting tracer studies in accordance with the law of conservation of mass, it follows that part of the indicator flows into the matrix. The linear dimensions of the flow region depend on the filtration-capacitive properties of the high-permeability channel and the matrix. From the solution of the diffusion equation, it follows that the initial concentration of the tracer decreases. Let us assume that there are several channels of the LFR between the injection and production wells. If several outputs of the indicator of different concentrations are recorded, then it follows that the channel trajectories have a complex position of the oil-saturated formation thickness (curvilinear).

The screening capacity of a disjunctive fault is determined by the displacement of rocks and the proximity of permeable and impermeable layers on both sides of the fault. In the work [26] the authors divide the screening capacity of faults into three categories. The first is the complete absence of conductivity along the fault, the existing numerous deviations of layers and a pronounced contact of permeable layers on one side of the fault with impermeable layers on the other side of the fault. The second is the existing permeability of the internal fault zone the and flow along it, regardless of the amplitude of the displacement. The third is characterized by the ratio of tangential and normal stresses to the plane of the fault. It determines the possibility of activating a fault which was originally a screen, with new mechanical effects on the rock mass and, accordingly, the emergence of the possible formation fluid filtration along it.

The screening capacity of faults in terrigenous rocks can be estimated from well logging data of adjacent wells by the value of the SGR coefficient – the proportion of clay in the main fault zone [57]. A fault is a screen with an SGR value of > 15–20 %. If the SGR value is less than 15 %, the screen has a fluid throughput capacity. However, in this work [27] for the Xingbei section of the Daqing field the minimum SGR value is indicated as 35 %.

The following should be noted: modern technologies that determine and map disjunctive faults cannot determine at specific sites whether these faults are screens, or whether they are channels for vertical fluid migration, or whether these disjunctive dislocations do not play a special role.

The authors of the work [14], based on the results of numerical modeling, conclude that taking into account the filtration structures of disjunctive faults is extremely

Table 2

Variants of interpretation models for production analysis

Well model	Layer model	Boundaries model (impermeable and constant pressure)
Vertical.	Homogeneous .	Infinite reservoir .
Inclining.	Double porosity.	One boundary.
With partly completion.	Double permeability .	Two parallel boundaries .
Horizontal.	Radial composite.	Two cross boundaries.
Vertical with FHF.	Line composite	Circle boundary.
Horizontal with FHF		Rectangular boundary

necessary when modeling well placement and purpose systems both in the case of faults with rock displacements on both sides and without such displacement. The implementation of design solutions that do not consider properties of disjunctive faults will certainly lead to significant losses in the current and final values of the oil recovery factor [20].

Without a doubt, the process of oil displacement by water will depend on the influence of the disjunctive faults filtration properties both in relation to the nature of filtration flows and the productivity factor of wells located between the faults [21–23].

However, work [14] indicates that known approaches which together ensure the identification of disjunctive faults, do not allow us to determine their role in the development implementation.

Taking into account predicted faults while forming a system for the placement and purpose of wells is possible based on development data [24]. For example, work [28] proposes an approach that allows us to determine the permeability, skin factor and drainage radius of a well in a reservoir. Its application requires constant values of bottomhole pressure, skin factor and well drainage zone.

There are known [59] mathematical models of the oil production process that describe the operating conditions of different well types, conditions at the outer boundary of the reservoir and different reservoir models. However, Table 2 shows that cases of finite or ultra-high fault permeability of a fault have been studied when a zone of fissured or fractured reservoirs is located near the fault. Thus, for application at sites with fault types of a more complex structure than a simple impermeable boundary, a comprehensive analysis of the development is required using field measurement data (oil, gas and water flow rates) and the results of hydrodynamic studies.

Solving problems taking into account disturbances in the case of two-phase filtration is significantly complicated, and obtaining simple analytical solutions is almost impossible. When creating a numerical model, it will be necessary to use all the a priori information, take into account the results of calculating bottomhole pressures and flow rates, comparing them with the results of field measurements, and specify the complex structure of the zone of dynamic influence of the disturbance [59]. A method of passive hydraulic interference is known, which is most informative when there is noticeable interference between wells when maintaining reservoir pressure by pumping water. Technical and software tools have appeared that make it possible to implement such "passive" hydraulic interference in large volumes [23, 56], since an increasing number of wells are equipped with constantly operating pressure sensors at the bottomhole and flow rate at the wellhead [32, 36, 48, 49]. That is, it has become possible, under favorable conditions, to evaluate not only the parameters of the formation itself, but also the characteristics of the hydrodynamic barrier between wells [31]. By using special methods and programs for processing time series of measurement data, it is possible to obtain information on hydrodynamic connectivity [33–47]. The scheme for analyzing long-term pressure measurements [50] conducted by permanent downhole sensors, published in 2006, makes it possible to solve a number of practical problems of reservoir studies using developed algorithms and processing programs [32, 51–55]. However, the narrow-band nature of disjunctive faults and their partial conductivity complicate the interpretation models when studying them using hydrodynamic well testing methods. This is due to the zonal structure of the reservoir region adjacent to the fault (composite model) [58, 59]. In the work [60] one of the variants of a multi-zone model is considered where the second zone is narrow. To determine the geological and physical characteristics of formations, the existing filtration parameters of various disturbances there, one can use the entire set of integral indicators (accumulated water and oil flow rates), the history of individual wells (absolute values of water and oil flow rates, their dependence on time). Unfortunately, these data become informative and reliable only some time after the objects are put into development when the well stock has already been formed. In such cases, adjusting the location of wells taking into account the presence of disturbances and their properties is almost impossible for financial and administrative reasons. This problem will be solved by developing a domestic software product for the complete analysis of long-term measurements of well temperature and pressure parameters. Tracer studies are very useful for identifying disturbances and highly permeable zones extending along them. However, positive results of these data can only be interpreted at a qualitative level. And for the correct interpretation of disturbances by tracer methods, it is necessary to significantly clarify both the methodology for their implementation and to carry out a significant amount of numerical experiments on formation models that take into account the filtration structure and parameters of disjunctive disturbances. The well-known results of the research conducted by the Institute of Systems Research of the Russian Academy of Sciences [14] on considering the identified disjunctive faults during the design and optimization of development clearly demonstrate (despite the differences in opinions of various authors) that the well placement system should be selected exclusively in accordance with the dislocation of the fault system taking into account the values of the filtration parameters of the faults themselves and the formations adjacent to these faults. The well grid becomes largely irregular.

It is indisputable that making a decision to revise the well placement and purpose system will be very difficult and will lead to an increase in economic costs. However, such a decision can only be made if ignoring the faults leads to a significant deterioration in the technological and economic indicators of development.

A pattern has been identified [10] that technological efficiency is manifested in injection wells which bottomholes are located in zones of maximum concentration of faults and cracks.

As a result, the obtained conclusions are confirmed: injection of sediment-forming systems must be carried out in those injection wells whose bottomholes are also located in flexural-fracture faults and dynamo-stressed zones; treatment of the bottomhole formation zone in fault zones is ineffective; it must be carried out in those wells that are located in zones without flexural-fracture faults and dynamo-stressed zones.

To justify the drilling system with flat and horizontal wells and to increase the efficiency of isolating water inflows from complex oil deposits based on field studies of their hydrodynamic state, the following scheme of an integrated approach is proposed:

– identifying areas of flexural-fracture faults, dynamically stressed zones and channels of low filtration resistance using indicator studies;

– locating intervals of opening productive formations by production wells at the maximum possible distance from flexural-fracture faults, dynamically stressed zones and channels of low filtration resistance;

– while opening the said zones with flat and horizontal wells, perform preliminary injection of plugging systems through injection wells with subsequent selective water isolation of the oil-water-saturated near-wellbore part of production wells.

Conclusion

1. Thus, an increase in the period of profitable application of oil field flooding is possible with a predictable accounting of the structural hydrodynamic heterogeneity of the formations caused by the presence of natural fractures and the technogenical formation of the NFS channel network.

2. A method for predicting the geometry of fracture formation has been developed, complementing the known hydrodynamic model of a reservoir system with arbitrary geological and physical properties.

It implements a step-by-step variation analysis of the hydrodynamic situation in the studied section of the formation and takes into account the stress arising due to pore viscous friction during filtration, rock stress in compression and tension as well as the elastic properties of the formation skeleton.

3. It has been revealed that a high value of injection pressure and excess pressure gradients over the critical value are not necessary and sufficient for infinitely long development of cracks due to both pressure losses during filtration in cracks and the equalization of the distribution of reservoir pressure with distance from the injection zone. It has been established that the development of a fracture network is caused by the formation of low reservoir pressure zones in the area of the future injection well with a minimum pressure at the point to which the fracture tends to pass from the subsequent injection zone.

4. In order to increase the period of profitable operation of wells, it is proposed to transfer production wells located on the periphery of the fracture network to injection. To ensure the efficiency of selection by horizontal wells, their feed contours should be supported by a network of technogenical fractures.

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