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Article / Статья

Forecasting the placement of horizontal and directional wells depending on the geological structure of the low-permeability formation YUS2

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Прогнозирование размещения горизонтальных и наклонно направленных скважин в зависимости от особенностей геологического строения низкопроницаемого пласта ЮС2

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Keywords:
horizontal wells, directional wells, geological characteristics, statistical analysis, low-permeability formation.

This study investigates the construction of a probabilistic-statistical model using two reference areas of field X, drilled with horizontal and deviated wells. The model involves discriminant analysis combined with the development of both linear and multivariate regression relationships to predict well locations within the undrilled area and potentially forecast initial oil production rates.
The impact of geological structure on well placement is analyzed using a t-test for comparing means. Based on identified differences in the geological structure at well locations, discriminant analysis was conducted to determine the factors influencing well type selection. The analysis revealed that the areas differ in geological structure, and porosity, permeability, and sand content of the formation influence the placement of horizontal and deviated wells.
Linear and multivariate regression analysis was performed to classify the territory into zones with distinct geological structures. Linear regression analysis indicated that oil production rates in low-permeability reservoirs are differentiated into three classes with varying parameter influences within each production rate range. Multivariate regression analysis enabled the assessment of the combined influence of the most statistically significant formation characteristics on oil production rates and provided multivariate regression equations for predicting oil production rates of horizontal and deviated wells.

Ключевые слова:
горизонтальные скважины, наклонно направленные скважины, геологические характеристики, статистический анализ, низкопроницаемый пласт.

Рассматривается построение вероятностно-статистической модели на примере двух эталонных участков Федоровской площади, разбуренных горизонтальными и наклонно направленными скважинами. Модель включает проведение дискриминантного анализа в сочетании с построением как линейных, так и многомерных регрессионных зависимостей для прогнозирования мест заложения скважин в пределах неразбуренного участка и возможности прогноза начальных дебитов нефти.
Влияние геологического строения на размещение скважин анализируется с использованием *t*-критерия Стьюдента для сравнения средних значений. На основе выявленных различий в геологическом строении в местах пробуренных скважин был проведен дискриминантный анализ для определения факторов, влияющих на выбор типа скважин. Анализ показал, что участки отличаются по геологическому строению, а на размещение горизонтальных и наклонно направленных скважин влияют пористость, проницаемость и песчанистость пласта.
Для типизации территории на зоны с различным геологическим строением был проведен линейный и многомерный регрессионный анализ. Линейный регрессионный анализ показал, что дебиты нефти в низкопроницаемых коллекторах дифференцируются на три класса с различным влиянием каждого параметра в каждом диапазоне дебитов. Многомерный регрессионный анализ позволил оценить комплексное влияние наиболее статистически значимых характеристик пласта на дебиты нефти и получить уравнения многомерной регрессии для прогнозирования дебитов нефти горизонтальных и наклонно-направленных скважин.

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Introduction

In different papers a comprehensive research of the geological structure of low-permeability formations is suggested, as the well flow rates in such objects largely depend on it [1–6]. In this study, two reference areas of the low-permeability formation YUS2, located in the northwestern and southeastern parts of the Fedorovskaya field, were selected for analysis (Fig. 1).

For the initial study of the geological structure influence on the horizontal and directional wells location, the following geological formation characteristics were considered: porosity (K_{por}, %), permeability (K_{perm}, 10^{-3} μm^2), sandiness (K_{sand}, fraction units), effective oil-saturated thickness of the formation ($h_{eff.o.sat}$, m), and absolute elevation of seam roof (A.e, m) in the northwestern and southeastern parts of the Fedorovskaya area [7–13]. The sample included 34 directional wells and 11 horizontal wells. Based on different studies, it is assumed that the listed formation characteristics significantly effect the horizontal and directional wells location [14–16]. To verify this, analyses were performed using the Student's t-criterion and the χ^2 criterion, and the average values of the geological characteristics were calculated, the results of which are presented in the table.

The average values analysis shows that the geological characteristics of the well groups statistically reflect the differences in geological structure at the sites of horizontal and directional wells.

It is noteworthy that the hypsometric position does not influence the horizontal and directional wells location. At the same time, directional wells are located in the porous sections of the formation with better filtration properties, as well as in areas of increased effective oil-saturated thicknesses compared to horizontal wells. It proves that the differentiation in drilling between horizontal and directional wells occurs due to these parameters. Therefore, it is necessary to forecast further drilling in the area, focusing on them.

Study of the geological structure influence on well flow rates using probabilistic-statistical methods

Confirmation of the hypothesis regarding the geological structure influence on the horizontal and directional wells location allows us to put forward the hypothesis that geological structure also affects their flow rates. Moreover, in each range of oil flow rates, various geological characteristics play a key role [17–20].

To study the mutual influence of geological characteristics on oil production, linear regression equations were constructed for a sample sorted by increasing production rates. A total of five dependencies were constructed: $q_{sat} = f(K_{por})$, $q_{sat} = f(K_{perm})$, $q_{sat} = f(K_{sand})$, $q_{sat} = f(\text{A.e})$ and $q_{sat} = f(h_{eff.o.sat})$. The first model was built based on three ($n = 3$) tests of oil flow rate, starting with its minimum values. The next model included data from four ($n = 4$) tests of well flow rates, and so on up to the last well in the sample ($n = 34$).

Based on the obtained values of free terms, angular coefficients for K_{por}, K_{perm}, K_{sand}, A.e, significance levels and Student's t-criteria of the regression equations, corresponding graphs of oil flow rate dependence on the listed parameters for each geological characteristic were constructed (Fig. 2–6).

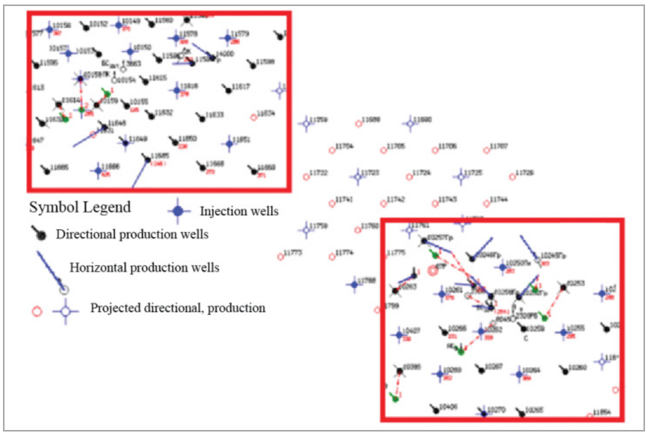


Fig. 1. Well location diagram

Average values of geological characteristics

Parameter	Average of horizontal wells	Average of directional wells	t – criterion / p-level / χ^2-criterion
K_{por}, %	15.3	17.7	4.1 / 0.0001 / 17.1
K_{perm}, 10^{-3} μm^2	5.2	10.7	3.7 / 0.0005 / 11.73
K_{sand}, fraction units	0.33	0.43	4.0 / 0.002 / 10.4
$h_{eff.o.sat}$, m	6.5	8.6	2.7 / 0.009 / 5.71
A.e, m	–2657.5	–2667.1	–1.5 / 0.14 / 1.2

The obtained graphs specifically characterize the relationship between the open porosity coefficient and oil flow rate across different porosity ranges. Breaks, interruptions, and curvature on the graphs reflect changes in the pore space structure in various ranges and its effect on oil flow rate. Analyzing the graphs allows for the identification of three classes with varying influences of pore space on oil flow rate: the first class with a weak influence up to 20 tons/day, a medium influence ranging from 20 to 26 tons/day, and a strong influence from 26 to 36 tons/day.

The obtained graphs show the influence of the reservoir filtration properties on oil flow rates in different ranges. It can be noted that the formation permeability has no effect on oil flow rates up to 19 tons/day, however, its significance increases for wells with oil flow rates ranging from 19 to 36 tons/day.

Based on the obtained graphs, it can be concluded that the influence of sandiness is similar to that of porosity: there are zones of weak influence up to 20 tons/day, where the oil flow rate is controlled by other geological factors; zones of medium influence ranging from 20 to 26 tons/day; and zones of strong influence from 26 to 36 tons/day.

Based on the obtained results, it can be concluded that the hypsometric position of the reservoir roof does not have a significant effect on oil flow rates at different ranges, since the significance level at any oil flow rate is greater than $p = 0.05$.

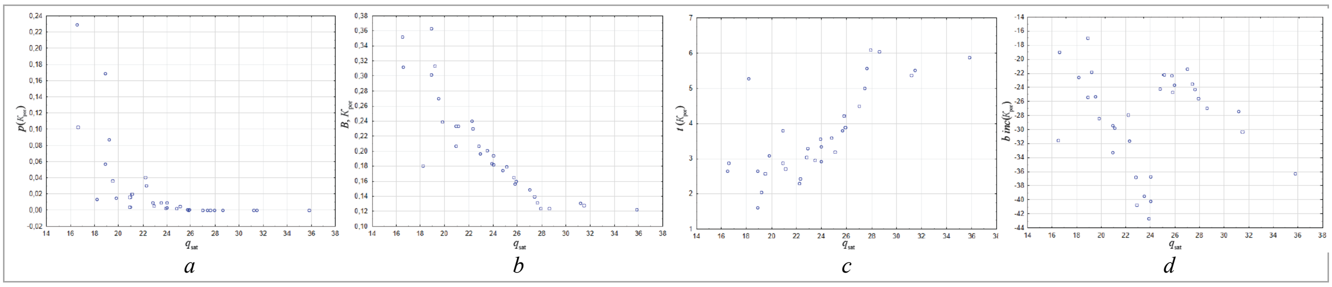


Fig. 2. Variation of values: *a* – significance level; *b* – angular coefficient; *c* – *t*-criterion; *d* – free term in the regression equations $q_{sat} = f(K_{por})$

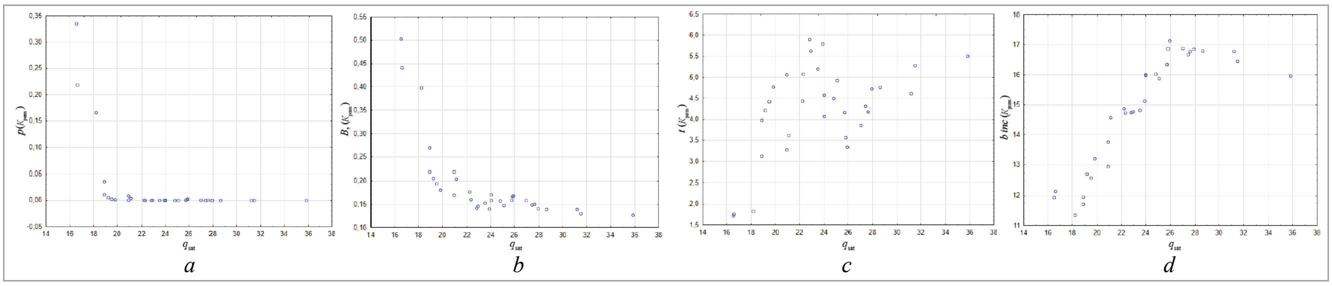


Fig. 3. Variation of values: *a* – significance level; *b* – angular coefficient; *c* – *t*-criterion; *d* – free term in the regression equations $q_{sat} = f(K_{perm})$

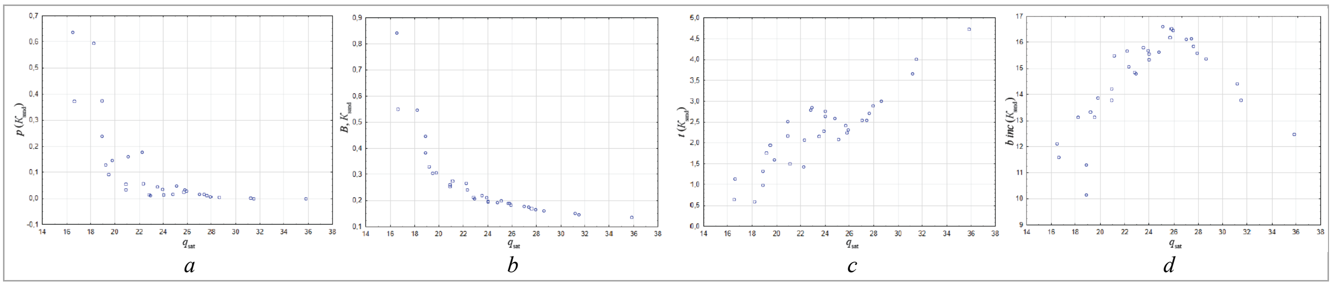


Fig. 4. Variation of values: *a* – significance level; *b* – angular coefficient; *c* – *t*-criterion; *d* – free term in the regression equations $q_{sat} = q_{sat} = f(K_{sand})$

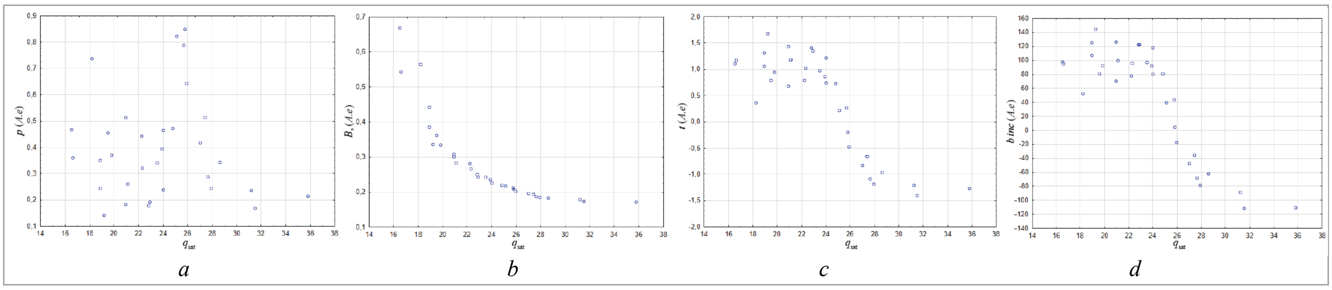


Fig. 5. Variation of values: *a* – significance level; *b* – angular coefficient; *c* – *t*-criterion; *d* – free term in the regression equations $q_{sat} = q_{sat} = f$(A.e)

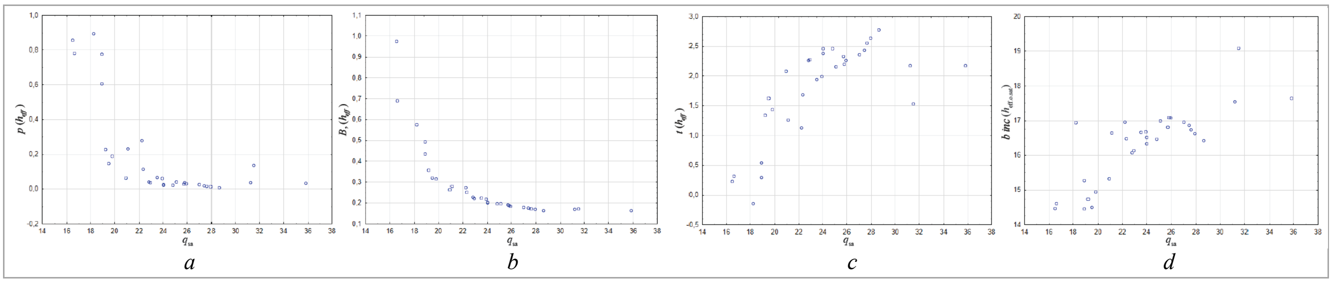


Fig. 6. Variation of values: *a* – significance level; *b* – angular coefficient; *c* – *t*-criterion; *d* – free term in the regression equations $q_{sat} = q_{sat} = f(h_{eff.o.sat})$

From the obtained graphs, there can be observed the zones of influence of effective oil-saturated formation thickness on oil flow rates: a zone of weak influence up to 24 tons/day; a zone of strong influence from 24 to 30 tons/day; and a zone of medium influence from 30 to 36 tons/day.

Thus, as a result of analyzing all geological characteristics, three zones of geological structure influence on well flow rates can be distinguished: a zone of weak influence (up to 20 tons/day), the range of flow rates can be classified as low-flow wells; a zone of medium influence (20–26 tons/day), corresponding to the medium-flow class; and a zone of strong influence (26–36 tons/day), for high-flow wells.

The obtained results correlate with the works of many researchers studying the influence of geological structure on well flow rates in low-permeability formations [21–25].

To assess the complex influence of geological characteristics on oil flow rates, a multivariate regression dependence was constructed, with all oil flow rates included in the model ($n = 34$). Thus, the first equation included only one geological parameter ($m = 1$), the second one – two parameters ($m = 2$), and so on until all parameters were included in the analysis ($m = 5$). As a result of including all variables in the multivariate regression analysis, the following equation was obtained [26–30]:

$$q_{\text{sat.init.}} = -116.9 + 1{,}39 \cdot K_{\text{por}} + 0.32 \cdot K_{\text{perm}} + 21.46 \cdot K_{\text{sand}} - 0.37 \cdot h_{\text{eff}}, (r = 0.87).$$

The geological parameters obtained in the equation have the greatest influence on oil flow rates. To assess the modeling reliability, calculations of oil flow rates were performed using the derived formula, compared with the actual flow rates (Fig. 7, *a*). A graph showing the dependence of the correlation coefficient r on various ranges of oil flow rates was also constructed (Fig. 7, *b*). The assessment methodology was as follows: at the first step of the analysis, the model included five flow rate definitions ($n = 5$), at the next step, six definitions ($n = 7$), and so on, until all definitions were included in the model ($n = 34$).

According to the data presented in Fig. 6, it can be observed that for low-flow wells with weak geological structure influence, the accumulated correlation decreases from 0.98 to 0.78 units. With the transition to the zone of medium and high-flow wells, the value of the accumulated correlation increases from 0.78 to 0.88 units, indicating a greater efficiency of the obtained model.

To study the mutual influence of geological characteristics on the oil flow rate of horizontal wells, linear regression equations were constructed for a sample sorted by increasing flow rates, similarly for directional wells.

Based on the obtained free terms values, angular coefficients, significance levels and Student's *t*-criteria of regression equations for K_{perm}, $H_{\text{eff.o.sat}}$, K_{por}, K_{sand}, corresponding graphs were constructed to show the dependence of oil flow rates on the listed parameters for each geological characteristic (Fig. 8).

The obtained results indicate the influence of sandiness over the entire range of oil flow rates in the presented sample while the porosity and permeability effects are weaker. These factors, in turn, impact the well flow rates starting from 40 tons per day. In general, for the group of horizontal wells, it is possible to identify a zone of low-flow wells with a weak influence of geological structure in the range of 20–40 tons/day. Conversely, high-flow wells show a strong influence from the geological structure, with oil flow rates exceeding 40 tons per day.

Thus, the most statistically significant parameters for determining the oil flow rate of horizontal wells are K_{perm}, K_{por} and K_{sand}. In this regard, it is necessary to use multivariate regression analysis, which allows us to evaluate the complex effect of these parameters on the oil flow rate.

The complex characteristics influence is assessed by constructing multiple regression equations and analyzing the cumulative correlation. The graphical representation of the results is illustrated in Fig. 9.

The obtained results indicate that the model has good prognostic properties, since the correlation coefficient is high at all ranges of oil flow rates of more than 0.92 units [31–34]. Also, the obtained regression equation can be used to assess the forecasted flow rates of horizontal wells.

$$q_{\text{sat.init.}} = -318{,}8 + 3{,}13 \cdot K_{\text{perm}} + 18{,}61 \cdot K_{\text{por}} + 43{,}53 \cdot K_{\text{sand}}$$

at $r = 0.96$.

Justification of the horizontal and directional wells location

In many works, the geological structure influence on the method for developing low-permeability reservoirs, using both horizontal and directional wells, is noted.

To comprehensively assess the geological structure influence on the well location, it is proposed to conduct linear discriminant analysis with stepwise inclusion of variables. The method allows for the gradual introduction of variables into the model, one by one, each time selecting the variable that contributes the most to the discrimination [31–35]. As variables for the discriminant analysis, the previously described geological characteristics of the reservoir were used; therefore, the total volume of the training sample consisted of 45 wells from the two reference areas.

As a result of the analysis, the following model was obtained, which includes two discriminant functions:

$$\text{Root1} = -8.55 + 0.343 \cdot K_{\text{por}} + 0.094 \cdot K_{\text{perm}} + 4.337 \cdot K_{\text{sand}}$$

at $R^2 = 0.593$, $\chi^2 = 25.98$, $p = 0.0002$;

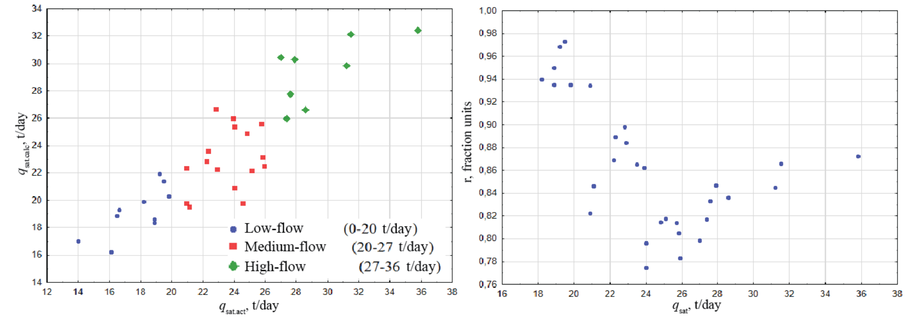
$$\text{Root2} = 20.42 - 1.337 \cdot K_{\text{por}} + 0.269 \cdot K_{\text{perm}} + 0.833 \cdot K_{\text{sand}}$$

at $R^2 = 0.411$, $\chi^2 = 7.77$, $p = 0.02$.

The obtained functions are statistically significant, as confirmed by the significance level and the χ^2 values. Based on the statistical parameters, it can be concluded that the most statistically significant function is Root 1, which is also evident in the graph of the discriminant function roots.

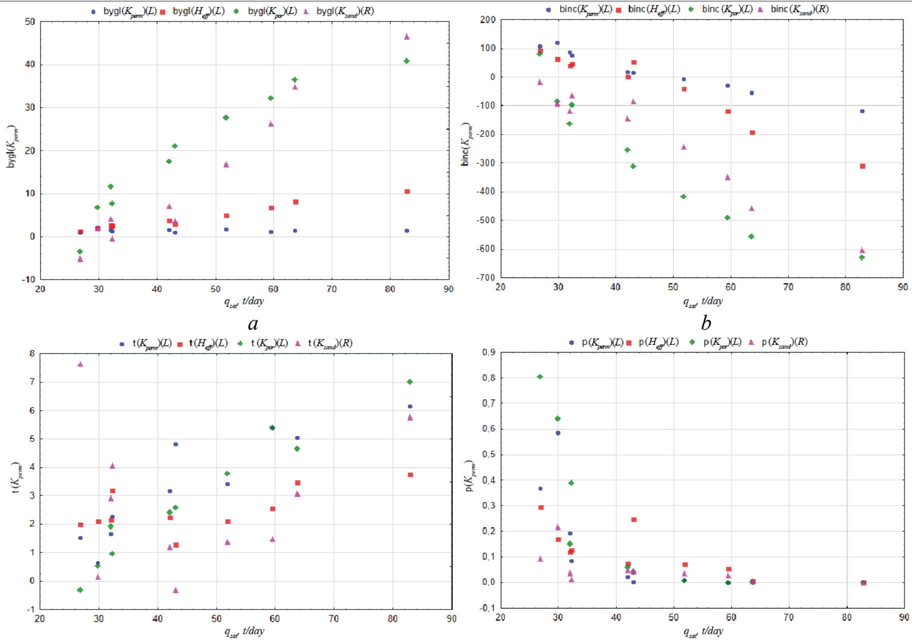
Among all the directional wells, 94.1 % were classified correctly, while the accuracy in horizontal wells reaches 75 %, indicating a high reliability of the obtained model.

As a result of the sequential inclusion of all proposed geological characteristics in the discriminant analysis, it can be observed that the equation is formed on the sequential arrangement of the most significant



a *b*

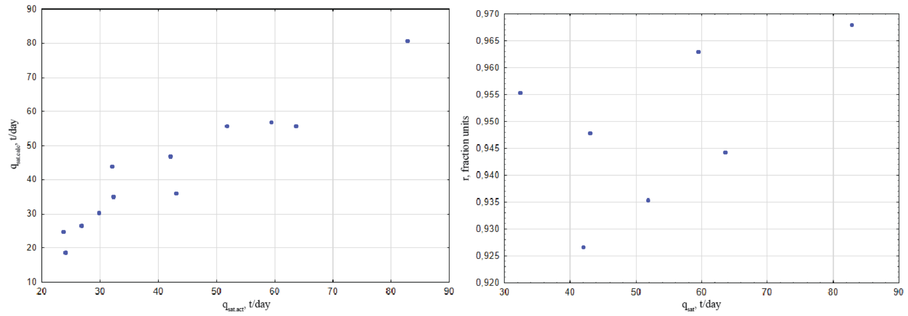
Fig. 7. *a* – Correlation field between calculated and actual oil flow rates;
b – graph of the correlation coefficient variations in different ranges of oil flow rate



a *b*

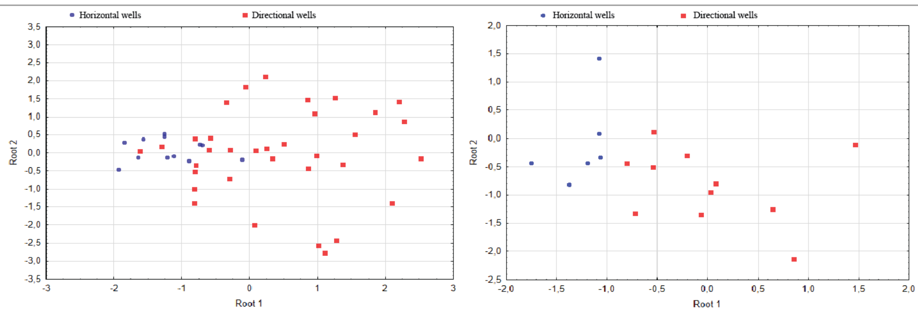
c *d*

Fig. 8. Variation in values: *a* – angular coefficient; *b* – free term;
c – *t*-criterion; *d* – significance level in regression equations q_{sat} = q_{sat} = $f(K_{perm})$, $f(H_{eff.o.sat})$, $f(K_{por})$, $f(K_{sand})$



a *b*

Fig. 9. Correlation field between calculated and actual oil flow rates (*a*);
graph of the changes in the correlation coefficient variation across different ranges of oil flow rate (*b*)



a *b*

Fig. 10. Graph of the discriminant functions roots: *a* – reference section; *b* – forecast section

geological parameters influencing the wells classification. In the first step, the K_{por} parameter is included, followed by K_{perm} and K_{sand} [36, 37]. The analysis performed allows us to statistically substantiate the discrimination of wells into horizontal and directional, based on their geological structure, and also to classify the undrilled section (Fig. 10).

Within the forecast area, out of the 17 planned wells, 6 were classified as horizontal and 11 as directional based on the obtained linear discriminant functions (Fig. 11).

On the presented map, two zones with different probabilities can be identified. The first zone ($p < 0.5$) corresponds to observations related to horizontal wells, while the second zone ($p > 0.5$) is characterized by observations related to directional wells. These zones were determined on the posterior probabilities of well classification, clearly demonstrating the probability distribution for different types of wells in the studied area [38–41].

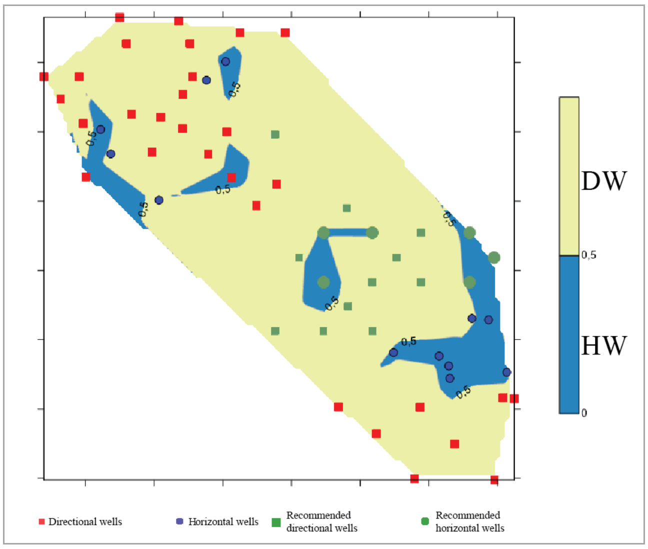


Fig. 11. Posterior probability distribution map

Conclusion

The study presents a comprehensive research of geological structure influence on the distribution and flow rates of horizontal and directional wells, using the low-permeability formation of the YUS2 of the Fedorovskoye field as an example.

The results of the discriminant analysis showed that the geological structure has a significant impact on the well location. The most significant geological characteristics influencing the location are the porosity, permeability and sandiness of the formation. Classification of wells by these parameters allowed for dividing them into horizontal and directional with high accuracy, confirming the high model reliability.

Analysis of linear and multivariate regression dependencies showed that the influence of geological characteristics on oil flow rate varies significantly across different flow rate ranges. For low-flow wells (up to 20 t/day) the impact of geological structure is minimal, whereas for medium-flow (20–26 t/day) and high-flow (26–36 t/day) wells, it increases significantly. In horizontal wells, sandiness proved to be the most influential characteristic over the entire oil flow rate range, while porosity and permeability become a more significant factor at flow rates exceeding 40 tons per day.

Multivariate regression analysis confirmed that the most statistically significant parameters for determining the oil flow rate in horizontal wells are porosity, permeability and sandiness. In directional wells the effective oil-saturated formation thickness also has an effect. The constructed regression equations and the analysis of accumulated correlation demonstrated the high forecast ability of the obtained models with the correlation coefficient of over 0.92 units for all oil flow rates ranges in horizontal wells and more than 0.78 units in directional wells.

The conducted research justifies the comprehensive approach to studying the geological structure of low-permeability reservoirs for the rational field development planning. The obtained results can be used for oil flow rates forecast and selecting optimal drilling locations, as confirmed by the high accuracy and reliability of the developed models.

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