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Development of Zone Forecast Probability Models for Oil and Gas Potential in the Central Part of the Permian Uplift by Structural and Capacity Criteria

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Разработка вероятностных моделей зонального прогноза нефтегазоносности центральной части Пермского свода по структурно-мощностным критериям

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The task to which this article is devoted has not received due attention in recent years, since the preparation of structures for deep drilling is carried out using seismic exploration. At the same time, there is a huge array of data on structured drilling, unfortunately, it has not been fully used. Thus, the goal of the study is to use data on structured drilling to solve not only structural problems for marking surfaces, but also more complex ones related to zonal oil and gas potential of territories.

The forecast of oil and gas content for marking and oil and gas horizons was carried out in three zones of oil and gas geological zoning. Using the data on these territories, studies were carried out to build probabilistic models for the zonal forecast of oil and gas content. To substantiate the joint use of data on marking surfaces and data on the tops of oil-bearing horizons, materials pertaining to 447 deep wells were studied.

Probabilistic models of zonal forecast of oil and gas content of the central part of the Permian uplift were developed according to structural and capacity criteria. The complex use of data on the absolute marks of deep and structured wells made it possible to rank the territory of the central part of the Permian uplift by the degree of zonal oil and gas content.

The Severokamskoye (0.73), Krasnokamskoye (0.67), Baklanovskoye (0.67), Polaznenskoye (0.67), Rassvetnoye (0.64) and Mezhevskoye (0.63) fields were characterized by the maximum values of P_{com}. For the Kozubaevskoye field, the P_{com} was 0.57. The Gorskoye, Lobanovskoye, Talitskoye, Zorinskoye and Shemetinskoye fields were characterized by the minimum values of P_{com}, varying in the range of 0.51–0.53. This scheme can be used when designing prospecting and exploration works in this area.

Ключевые слова:
нефтегазогеологическое районирование, вероятностно-статистические критерии нефтегазоносности, нелокализованные ресурсы нефти, визейский терригенный нефтегазоносный комплекс, структурно-мощностные критерии, коэффициент корреляции, вероятность, нефть, поисково-разведочные работы, структурные скважины, маркирующие поверхности, зоны районирования, статистический анализ, сейсморазведка, абсолютная отметка.

Задаче, которой посвящена данная статья, в последние годы не уделяется должного внимания, так как подготовку структур к глубокому бурению производят с помощью сейсморазведки. В то же время имеется огромный массив данных по структурному бурению, к сожалению, используются не полностью. Таким образом, актуальность применения данных по структурному бурению для решения не только структурных задач по маркирующим поверхностям, но и более сложных, связанных с зональной нефтегазоносностью территорий, не вызывает сомнений.

Прогноз нефтегазоносности по маркирующим и нефтегазоносным горизонтам проводился в трех зонах нефтегазогеологического районирования. С использованием данных по этим территориям выполнялись исследования для построения вероятностных моделей зонального прогноза нефтегазоносности. При обосновании совместного использования данных по маркирующим поверхностям и данных по кровлям нефтесодержащих горизонтов исследовались материалы по 447 глубоким скважинам.

Разработаны вероятностные модели зонального прогноза нефтегазоносности центральной части пермского свода по структурно-мощностным критериям. Комплексное использование данных по абсолютным отметкам глубоких и структурных скважин позволило ранжировать территорию центральной части Пермского свода по степени зональной нефтегазоносности.

Максимальными значениями $P_{КОМ}$ характеризуются Северокамское (0,73), Краснокамское (0,67), Баклановское (0,67), Полазненское (0,67), Рассветное (0,64) и Межевское (0,63) месторождения. Для Козубаевского месторождения $P_{КОМ}$ равно 0,57. Горское, Лобановское, Талицкое, Зоринское и Шеметинское месторождения характеризуются минимальными значениями $P_{КОМ}$, изменяющимися в интервале 0,51–0,53. Эти данные могут быть использованы при проектировании поисково-разведочных работ.

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Introduction

Probabilistic methods were used in a number of studies for the purpose of forecasting zonal and local oil and gas potential [1–17]. It is worth noting that a whole range of geological events were predicted using probabilistic models across territories that are characterized by contrasting geological structures [3–50].

This article focuses on the task that has been largely neglected in recent years as the structures are prepared for deep drilling using seismic exploration. That said, there is a plenitude of information available on the data regarding structured drilling that is regrettably overlooked.

The purpose of the study is to demonstrate that the data on structured drilling can be of use when it comes to handling both structural problems in marking surfaces and more complex ones related to zonal oil and gas potential of territories. The task was carried out based on the survey of the central part of the Permian uplift that enjoys a vast array of data on marking horizons and oil-bearing strata. The oil and gas potential was forecast pertaining to marking surfaces and oil- and gas-bearing horizons across this area of the Permian uplift within the three zones of oil and gas geological zoning (Fig. 1). Zone 1.B.4 includes the Krasnokamsky (Severokamskoye and Krasnokamskoye oil fields) and Osinsky (Belyayevskoye field) arches (Fig. 1). This zone also includes the northwest and central areas of the Permian uplift; zone 2.A.3 spans across the Gorskoye, Rassvetnoye, Baklanovskoye, Kozubayevskoye, and Lobanovskoye fields. Zone 2.A.4 features the Talitskoye, Yuzhno-Mezhevskoye, Mezhevskoye, Polaznenskoye, and Shemetinskoye fields.

The study drew on the data about these territories to develop probabilistic models of zonal forecasts for the oil and gas potential. The combined usage of data on marking surfaces and tops of oil-bearing horizons was substantiated based on materials retrieved across 447 deep wells.

Grounds for Building Probabilistic Models to Forecast Zonal Oil and Gas Potential

The probabilistic models of zonal oil and gas potential forecasting were developed using the following absolute elevations of horizon tops and stages:

- Bobrikovsky horizon – C_1bb,
- terrigenous bench of Tula horizon – C_1tl_t,
- carbonate bench of Tula horizon – C_1tl_k,
- Bashkir stage – C_2b,
- Vereysky horizon – C_2vr,
- terrigenous bench of Artinsky stage – P_1ar_t,
- carbonate bench of Artinsky stage – P_1ar_k,
- Irensky horizon – P_1ir.

The first round of the statistical analysis centered around calculating the values of correlation coefficients r across all absolute elevations under study (Table 1).

The r values demonstrate that there are two groups that show significantly high correlation ratios within. The first group of high correlation ratios is found between the marking surfaces.There are significant direct correlation ratios (P_1ar_t, P_1ar_k, P_1ir). The second group with high correlation ratios can be seen across all oil- and gas-bearing horizons under study (C_1bb, C_1tl_t, C_1tl_k, C_2b, C_2vr). It is important to point out that the correlation ratios are low between the oil- and gas-bearing horizons and marking surfaces, statistically insignificant, and range from 0.01 to –0.33 (see Table 1). It means that using absolute elevations of marking surfaces for zonal oil and gas potential forecasting proves highly problematic across the entire territory of the central area of the Permian uplift. Therefore, the zonal forecasting models that draw on data from marking horizons were developed as differentiated across the areas of oil and gas geological zoning.

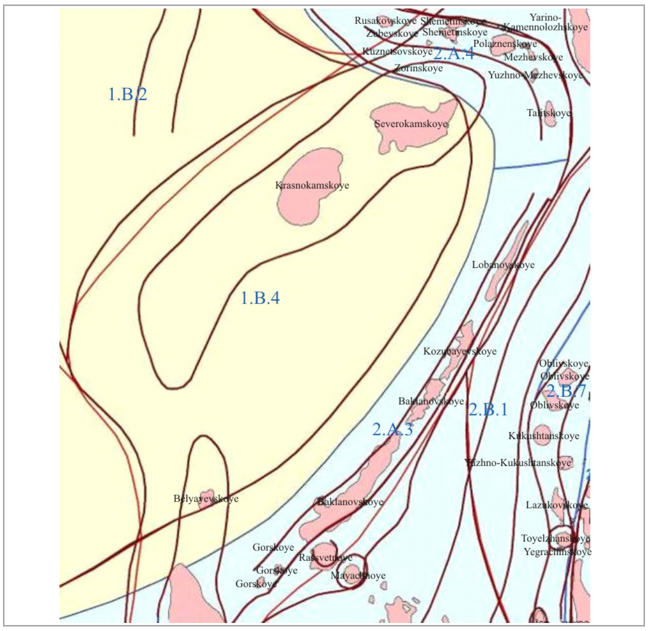

Fig. 1. Diagram of oil and gas geological zoning

The statistical models of zonal oil and gas potential forecasting were developed based exclusively on the data pertaining to the following absolute elevations:

- Vereysky horizon – C_2vr,
- terrigenous bench of Artinsky stage – P_1ar_t,
- carbonate bench of Artinsky stage – P_1ar_k,
- Irensky horizon – P_1ir.

It is predefined by two reasons: firstly, the Vereysky horizon in section is located in the closest proximity to marking surfaces; secondly, all oil- and gas-bearing horizons (C_1bb, C_1tl_t, C_1tl_k, C_2b, C_2vr) show positive statistically significant correlation ratios (r in the range from 0.94 to 0.99). Combining data on these horizons is not reasonable as the results are nearly identical. In addition, the study considered layer thickness between marking surfaces and the Vereysky horizon. The suggested technique of zonal oil and gas potential forecasting can be illustrated using data across the wells that are located within zone 1.B.4. Some statistical characteristics were defined for this zone (Table 2) using the data on the wells located within (Class 1) and outside the reservoir limits (Class 2). The values of layer elevations that mark the top of the Irensky and Vereysky horizons as well as the thickness of section between them – $m\,(vr\text{-}ir)$ are given in Table 2 as pertaining to the defined classes.

This shows that the absolute elevations of the top of the Irensky horizon within the reservoir limits are much higher that those outside the limits. The average value $H\,(ir)$ for Class 1 is 147.2 m higher than the average value for Class 2. To estimate how the average values vary in terms of $H\,(ir)$, we shall find the value of t criterion using the following formula:

$$t_p = \frac{|X_1 - X_2|}{\sqrt{\left(\frac{1}{n_1} + \frac{1}{n_2}\right)\left(\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}\right)}},$$

where X_1, X_2 stand for the average values of $H\,(ir)$ for Classes 1 and 2 correspondingly; and S_1^2, S_2^2 are mean square deviations.

The difference in average values is deemed statistically significant if $t_p > t_t$. Values t_t are determined depending on

Table 1

Correlation matrix

Parameter	$H(ir)$	$H(ar_t)$	$H(ar_k)$	$H(vr)$	$H(b)$	$H(tl_k)$	$H(tl_t)$	$H(bb)$
$H(ir)$	1.00	**0.98**	**0.98**	–0.30	–0.33	–0.13	–0.10	–0.16
$H(ar_t)$		1.00		–0.18	–0.21	–0.02	0.01	–0.05
$H(ar_k)$			1.00	–0.18	–0.21	–0.02	0.01	–0.05
$H(vr)$				1.00	**0.99**	**0.95**	**0.95**	**0.94**
$H(b)$					1.00	**0.95**	**0.94**	**0.94**
$H(tl_k)$						1.00	**0.99**	**0.98**
$H(tl_t)$							1.00	**0.98**
$H(bb)$								1.00

Note: Significant correlation coefficients are highlighted.

Table 2

Some statistical characteristics for Zone 1.B.4

Parameter	Average	St. dev.	Min.	Max.
Parameter		$H(ir)$, m		
Class 1	–7.1	55.9	–193.6	105.2
Class 2	–154.3	89.4	–336.1	54.0
Parameter		$H(vr)$, m		
Class 1	–822.9	23.5	–906.6	–789.1
Class 2	–901.6	44.8	–1007.6	–818.2
Parameter		$m(vr\text{-}ir)$, m		
Class 1	815.8	55.0	709.0	938.0
Class 2	747.3	69.3	660.0	907.0

Table 3

Distribution of values $H(ir)$

Item class	Variability range $H(ir)$									
	–350…–300	–300…–250	–250…–200	–200…–150	–150…–100	–100…–50	–50…0	0…50	50…100	100…150
Areas within the reservoir limits, n = 70				0.042		0.085	0.471	0.271	0.114	0.017
Areas outside the reservoir limits, n = 49	0.043	0.022	0.285	0.326	0.040	0.163	0.061	0.040	0.020	

the amount of compared data and level of significance (p = 0.05). Indicator $H(ir)$ is characterized by $t_p = 11.286$, p = 0.000000. It shows that the average values for $H(ir)$ are statistically different.

In order to estimate the probability of finding the oil and gas potential for this zone using $H(ir)$, an individual forecasting model was built using a technique that is described quite in detail in the study [1]. Let us take a brief look at the technique of building individual probabilistic models using $H(ir)$ as an example. This technique was applied to study the distribution density across both classes. The first case considers data pertaining to values of $H(ir)$. Within the territories of oil fields is Class 1, $n_1 = 70$, the second case draws on the data across the areas outside the reservoir limits, which is Class 2, n_2 = 49. Then the cumulative value (set) of $H(ir)$ should be divided into units belonging to Class 1. Following the applied technique, the first step of building a probabilistic model includes histograms that are drawn for Classes 1 and 2 based on the $H(ir)$ data. The optimal values of the $H(ir)$ range are found using the Sturges' rule:

$$\Delta X = \frac{X_{\max} - X_{\min}}{1 + 3{,}32 \cdot \lg N},$$

where $X_{\max}$ is the maximum value of the parameter, $X_{\min}$ is the minimum value of the parameter, N is the amount of data.

Frequencies are determined for each range:

$$P(X) = \frac{N_k}{N_g},$$

where $P(X)$ is a frequency in the k-th range for Group $K_{\text{выт}}$ (q = 1), q = 2 corresponds to Group $\text{К}_{\text{выт}}^{\text{мо}}$, N_k stands for the number of cases that contain indicator $P(X)$ within the k range, and N_q is the volume of samples for Classes 1 and 2. The ratios of the share of units that fell within different variability ranges of $H(ir)$ were processed using the interval analysis shown in Table 3.

It is clearly seen that, as it relates to oil- and gas-bearing areas, higher $H(ir)$ entails more frequent occurrence of values. It is worth noting that oil- and gas-bearing areas within the range of –350…–200 m do not show any values, whereas outside the oil- and gas-bearing reservoir limits the sum frequency of their detection stands at 0.341. The areas outside the oil- and gas horizon starting from the range of –200…–150 m demonstrate less frequent occurrence of values. The modal range for oil- and gas-bearing areas spans across –50…0 m, and the areas outside the oil- and gas-bearing limits range within –200…–150 m. While in the range of –350…–100 m the ratio of the first class occurrence frequency to the second class is 0.055, in the range of –100…150 m this ratio is much higher and stands at 3.373. It all shows that $H(ir)$ values are distributed noticeably differently across the classes under study. The quantitative difference in distribution of values was based on Pearson's chi-squared test χ^2 following the formula

$$\chi^2 = N_1 N_2 \sum_{i=1}^{e} \frac{1}{M_1 + M_2} \left(\frac{M_1}{N_1} - \frac{M_2}{N_2} \right)^2,$$

where N_1, N_2 are the number of $H(ir)$ values in Classes 1 and 2, respectively; M_1, M_2 are the number of values that fall within the set range in both classes correspondingly; e is the number of intervals.

The values of χ^2 as per parameter $H(ir)$ equal to 85.061 at p = 0.000000. It indicates that distribution densities are statistically different. Further, each range gets specified in terms of probabilities of affiliation with oil-

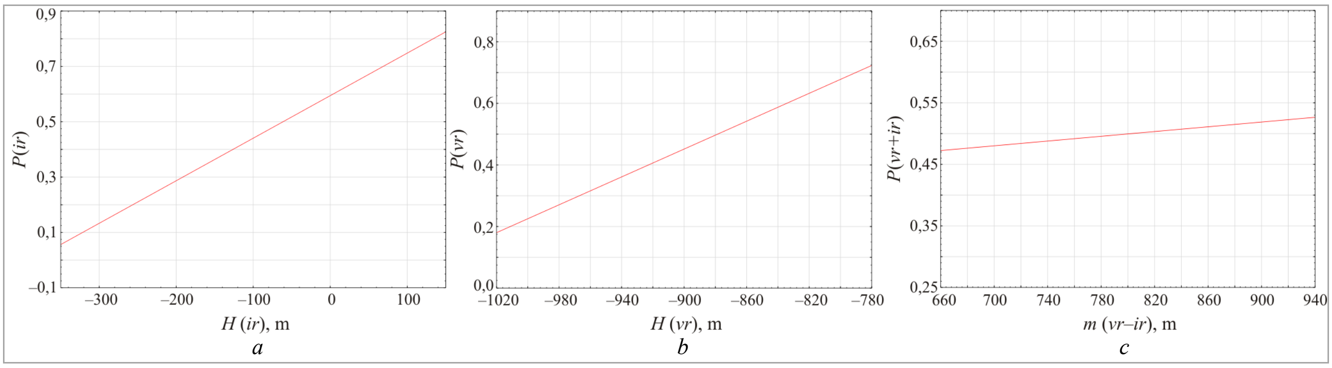

Fig. 2. Dependence: *a* – $P(ir)$ on $H(ir)$; *b* – $P(vr)$ on $H(vr)$; *c* – $P(vr\text{-}ir)$ on $m(vr\text{-}ir)$

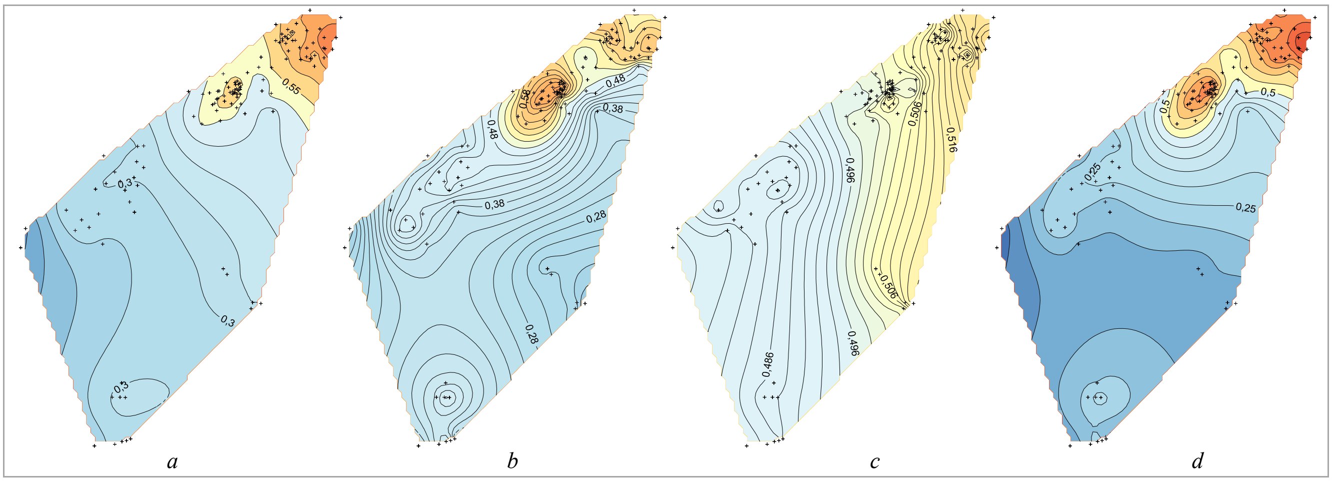

Fig. 3. Probabilistic diagram of oil and gas potential for Zone 1.B.4
as per parameter: *a* – $P(ir)$; *b* – $P(vr)$; *c* – $P(vr\text{-}ir)$; *d* – P_{COM} for Zone 1.B.4

Table 4

Distribution of P_{COM} values

Item class	Variability range, P_{COM}									
	0–0.1	0.1–0.2	0.2–0.3	0.3–0.4	0.4–0.5	0.5–0.6	0.6–0.7	0.7–0.8	0.8–0.9	0.9–1.0
Areas within the reservoir limits, n = 70		0.050				0.100	0.450	0.316	0.083	0.017
Areas outside the reservoir limits, n = 49	0.061	0.244	0.387	0.081	0.122	0.081	0.020			

bearing areas. The interval probabilities of affiliation with Class 1 are juxtaposed with average interval values of $H(ir)_{\text{и}}$. The values of $P(H(ir)_{\text{и}}$ and $H(ir)_{\text{и}}$ are used to calculate the matching correlation coefficient r and draw up a regression equation. The resulting model is further modified on the condition that the average value of probabilities for oil-bearing areas should exceed 0.5 and those outside the reservoir limits should be below 0.5.

The linear dependence of $P(ir)$ on $H(ir)$ is expressed in the following way: $P(ir) = 0.594 + 0.0015\ H(ir)$. The linear probabilistic models for other parameters are built the same way and quoted further in the article.

The visual representation of the model is given in Figure 2, *a*.

It is clear that whenever the values of $H(ir)$ oscillate from –336.1 to 105.2 m the value of $P(ir)$ rises from 0.09 to 0.75.

This model was used to calculate $P(ir)$ for wells within the zone, which were used for the probabilistic algorithm of oil and gas potential in Zone 1.B.4 (Fig. 3, *a*).

It follows that the maximum probabilities of zonal oil and gas potential are located in the northeast part of this zone. The values of $P(ir)$ for the Krasnokamskoye and Severokamskoye fields found within the zone stand at 0.59 and 0.74, respectively.

The top of the Vereysky horizon, as can be seen in Table 2, lies much higher within the oil- and gas-bearing limits than outside them. The model based on $H(vr)$ can be expressed the following way: $P(vr) = 2.488 + 0.0023\ H(vr)$. The visual representation of the model is given in Figure 2, *b*.

It shows that values of $H(vr)$ that change from –1007 to –789 m increase the value of $P(vr)$ from 0.17 to 0.67.

This model was the basis for the probabilistic algorithm of oil and gas potential for Zone 1.B.4 (Fig. 3, *b*).

The maximum probabilities are clearly seen to be located in the northeast part of this zone.

As shown in Table 2, the average value for the layer thickness between the Vereysky and Irensky horizons within the reservoir limits is higher (815 m) than that outside them (747 m). The probability of oil and gas potential in this zone can be expressed in the following way: $P(vr\text{-}ir) = 0.345 + 0.0002\ m(vr\text{-}ir)$. The visual representation of this dependence in shown in Figure 2, *c*.

Therefore, whenever values $m(vr\text{-}ir)$ go up from 660 to 938 m, it increases value $P(vr\text{-}ir)$ insignificantly from 0.47 to 0.53. This indicator is typically less informative than the structural ones.

This model was the basis for the probabilistic algorithm of oil and gas potential in Zone 1.B.4 (Fig. 3, *c*).

The data presented in Figure 3 *c* demonstrate that higher values of probability ($P(vr\text{-}ir) > 0.5$) are characteristic not only of the Severokamskoye and Krasnokamskoye fields but also of the territory to the south of them.

Development of a Comprehensive Model of Zonal Oil and Gas Potential Forecasting

The analysis of the resulting models suggests that they cover the oil and gas potential of this zone but the variability ranges of the probability values differ considerably. To apply the aforementioned parameters comprehensively, we shall use a composite indicator that is calculated using the following formula:

$$P_{\text{COM}} = \frac{\prod_{j=1}^{m} P(W_1|X_j)}{\prod_{j=1}^{m} P(W_1|X_j) + \prod_{j=1}^{m} \left(1 - P(W_1|X_j)\right)}$$

where $P(W_1/X_j)$ *stands for* respective probabilities: $P(ir)$, $P(vr)$ and $P(vr\text{-}ir)$.

The values of P_{COM} were set as a basis for the probabilistic algorithm of oil and gas potential for Zone 1.B.4 (Fig. 3, *d*). The P_{COM} values are distributed depending on the oil and gas potential of the territories and can be seen in Table 4.

The results in the table show that oil- and gas-bearing areas in 95 % of cases demonstrate $P_{\text{COM}} > 0.5$, whereas areas outside the reservoir limits are characterized by values below 0.5. The average value of $P_{\text{КОМ}}$ in oil- and ga-bearing areas stands at 0.679 ± 0.117, while outside the reservoir limits it is 0.309 ± 0.185, as per parameter *t* they differ statistically ($t = 13.368$; $p = 0.000000$). The value of parameter χ^2 as per indicator P_{COM} stands at 103.947 at $p = 0.000000$. It means that distribution densities of P_{COM} are statistically different.

It is also obvious that higher values of probability ($P_{\text{COM}} > 0.5$) are clearly characteristic of the Severokamskoye and Krasnokamskoye oil fields, and the former shows a higher probability (0.84) than the latter (0.73). The rest of the area in Zone 1.B.4. shows little promise in terms of exploring for oil and gas deposits, as the structural parameters suggest.

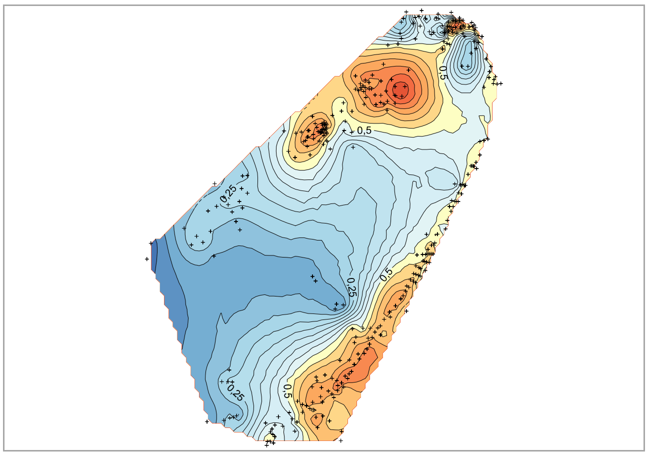

Fig. 4. Probabilistic algorithm of oil and gas potential based on indicator P_{COM} for the central part of Permian uplift

Conclusion

The discussed technique was used to build individual and comprehensive models of other areas in the central part of the Permian uplift. The models specified the values of P_{COM} across all wells, which were further used for the probabilistic algorithm of zonal oil and gas potential for the central part of the Permian uplift (Fig. 4).

The approach suggests that combined probabilities cover oil- and gas-bearing limits in all fields under study. The maximum values of P_{COM} are shown by the Severokamskoye (0.73), Krasnokamskoye (0.67), Baklanovskoye (0.67), Polaznenskoye (0.67), Rassvetnoye (0.64), and Mezhevskoye (0.63) fields. The Kozubayevskoye field showed P_{COM} of 0.57. The Gorskoye, Lobanovskoye, Talitskoye, Zorinskoye, and Shemetinskoye fields are characterized by minimum P_{COM} values that vary within the range of 0.51–0.53.

As a result, it can be concluded that the comprehensive application of data on absolute elevations of deep and structural wells facilitates the process of ranging the area of the central Permian uplift by order of zonal oil and gas potentials. This approach can be used in designing surveys and explorations in the territory under study.

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