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Probabilistic-Statistical Forecast of Oil and Gas Content of Local Structures on the Izhemsk Stage Territory

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Вероятностно-статистический прогноз нефтегазоносности локальных структур на территории Ижемской ступени

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probabilistic-statistical model, oil and gas potential forecast, prepared structures, oil and gas potential criteria, oil, complex criterion, Domanik horizon, conditional probability, discriminant analysis.

A methodology for predicting the oil and gas content of local structures using probable statistical methods on the territory of the Izhemsk stage is presented. The main oil and gas prospects in this area are associated with buried structures confined to the zone of Domanik barrier reefs. The goal of the work was to develop a comprehensive probabilistic model for assessing geological risks and ranking prepared structures according to the prospects of their introduction into deep drilling. The work analyzed the morphological parameters of the structures on the roof of the Domanik horizon: amplitudes, areas, absolute elevations of the arches, dimensions of the axes of the structures, as well as the thickness of the Domanik horizon and the distance of the structures from the deep-sea slope. To build probabilistic models, the initial data was divided into two classes: oil-saturated and empty structures. The information content of the selected indicators was assessed using Student's t-test. A statistical difference in the average values of the following parameters was established: amplitude, the size of the long axis of the structures, the thickness of the Domanik deposits and the distance of the structure's arch from the deep-sea slope. Also the least informative parameter – the absolute arch elevation was identified and excluded from further analysis. For a detailed analysis of the parameter values distribution, categorized histograms were constructed according to the classes of oil-saturated and empty structures. At the first stage, conditional interval probabilities were calculated for each parameter and individual probabilistic models of oil and gas content were built. At the second stage, all indicators were combined into a complex model. To assess the quality of the model, a categorized histogram of cosplay probabilities by structure class was constructed, and the obtained probabilities were compared with the results of discriminant analysis. It was established that the model successfully separated empty and oil-saturated structures according to the boundary value of the complex probability of 0.5 units. As a result of applying the constructed model, it was calculated that within the area under consideration, the most promising in terms of oil and gas content was the Pilegorskaya structure.

Ключевые слова:
вероятностно-статистическая модель, прогноз нефтегазоносности, подготовленные структуры, критерии нефтегазоносности, нефть, комплексный критерий, доманиковый горизонт, условная вероятность, дискриминантный анализ.

Представлена методика прогноза нефтегазоносности локальных структур вероятно-статистическими методами на территории Ижемской ступени. Основные перспективы нефтегазоносности на данном участке связаны с погребенными структурами, приуроченными к зоне барьерных рифов доманикового возраста. Целью работы является разработка комплексной вероятностной модели для оценки геологических рисков и ранжирования подготовленных структур по перспективности их ввода в глубокое бурение. В работе были проанализированы морфологические парметры структур по кровле доманикового горизонта: амплитуды, площади, абсолютные отметки сводов, размеры осей структур, а также толщины доманикового горизонта и удаленность структур от глубоководного склона. Для построения вероятностных моделей исходные данные разделены на два класса: нефтенасыщенные и пустые структуры. Информативность выбранных показателей оценена с помощью *t*-критерия Стьюдента. Установлено статистическое различие средних значений следующих параметров: амплитуда, размер длинной оси структур, толщина доманиковых отложений и удаленность свода структуры от глубоководного склона. Также выявлен и исключен из дальнейшего анализа наименее информативный параметр – абсолютная отметка свода структур. Для детельного анализа распределения значений параметров были построены категоризованные гистограммы по классам нефтенасыщенных и пустых структур. На первом этапе по каждому параметру были рассчитаны условные интервальные вероятности и построены индивидуальные вероятностные модели нефтегазоносности. На втором этапе все показатели объеденены в комплексную модель. Для оценки качества модели построена категоризованная гистограмма комплексных вероятностей по классам структур, а также проведено сопоставление полученных вероятностей с результатами дискриминантного анализа. Установлено, что модель успешно разделяет пустые и нефтенасыщенные структуры по граничному значению комплексной вероятности 0,5 доли ед. В результате применения построенной модели рассчитано, что в пределах рассматриваемой площади наиболее перспективной в отношении нефтегазоносности является Пильегорская структура.

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Introduction

In tectonic terms, the Izhma stage is a structure of the first order, located in the central part of the Izhma-Pechora syneclise. The Izhemskaya Stage is a monocline dipping gently in the northeastern direction. The main prospects of oil and gas bearing capacity in this area are associated with buried structures confined to the zone of barrier reefs of the pre-Domanic age, namely, the crest part of the reef, usually composed of permeable carbonate varieties, and the encircling structures of reef massifs of the Syrachoic age [1, 2].

During the Domanic period, as a result of abrupt submergence of the area under marine sedimentation conditions, an uncompensated deep-water depression existed in the southwestern part of the Izhemskaya Stage, bordered from the east and north by a winding strip of barrier reefs, beyond which sedimentation proceeded under shelf conditions. A chain of narrow anticlinal folds developed into the reef-forming zone, forming a rampart-like uplift along the deep-water slope.

Within the study area, commercial accumulations of hydrocarbons are associated with carbonate rocks of the Domanic-Tournaisian oil and gas complex. The Shchelyayurskoye, Demaelskoye, Makarielskoye, Verkhnevolminskoye, Nizevoye and Yuzhno-Nizevoye, Yuzhno-Sedmeskoye oil fields have been discovered here. The assessment of oil and gas potential is carried out in the Piliegorskaya area, within which there are three local structures prepared for deep drilling: Piliegorskaya, Voskresenskaya, Vostochno-Makaryelskaya. An extract from the tectonic zoning scheme is presented in Fig. 1.

Processing a large amount of various geological and geophysical information requires the use of methods of mathematical statistics and probability theory [3–12]. The mathematical apparatus used in the work and its application for solving predictive problems are given in [13–26].

In order to rank the prepared structures, the prediction of oil and gas occurrence was carried out by probabilistic-statistical methods the use of which is given in the works [27–38].

Construction of one-dimensional probabilistic models

To assess the prospects for oil and gas potential, the morphological parameters of the structures along the reflecting horizon IIIf2 confined to the roof of the Domanic horizon were analyzed: absolute elevations of the arched part of the structures – $AO_{св}$, m; amplitude – A, m; square – S, km^2; dimensions of long axis – $L_д$, m; dimensions of short axis – $L_к$, m. Also is is analyzed the thickness of the Domanic horizon within the structures – H_{dm}, m; distance of the structure vaults from the deep-sea trench – $L_{гс}$, km. For the construction of probabilistic-statistical models, the structures were divided into two classes: class 1 – structures with proven oil-bearing capacity; class 2 – structures with negative drilling results. The algorithm for building one-dimensional probabilistic models is described in [39–41].

To assess the informativeness of the selected parameters, we compared the mean values of parameters by classes of structures using Student's t-criterion. The comparison results are presented in Table 1.

Statistically different mean values of the parameters by classes were found in amplitude, size of the long axis of the structures, thickness of the domanic sediments, and distance of the structure vault from the deep-water slope. It was also revealed that the absolute elevation of the structure vault is the least informative parameter. Therefore, this parameter will not be used for building probabilistic models. To study the distribution of parameters in detail, categorized histograms by structure classes were constructed (Fig. 2).

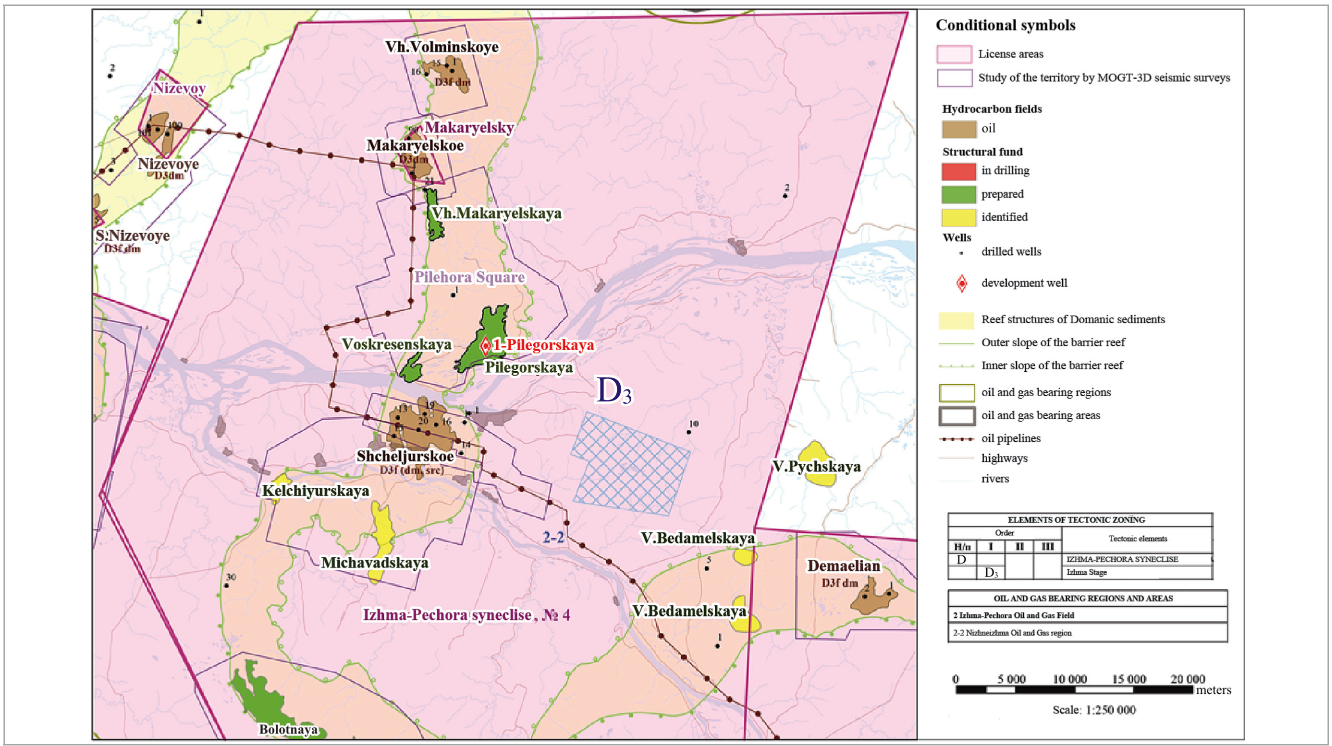

Fig. 1. Extract from the tectonic zoning scheme

Table 1

Statistical characteristics

Parameter	Average value		t-criterion / p-value
	Oil structures	Empty Structures	
AO_{sv}, m	–2054.29	–2056.57	0.04 / 0.97
A, m	34.14	20.00	3.91 / 0.002
S, km^2	6.03	3.99	1.49 / 0.162
L_d, km	4.10	3.42	1.14 / 0.275
L_k, km	2.36	1.39	2.97 / 0.012
H_{dm}, m	149.00	128.71	2.93 / 0.0127
L_{gs}, km	1.27	4.39	-2.87 / 0.014

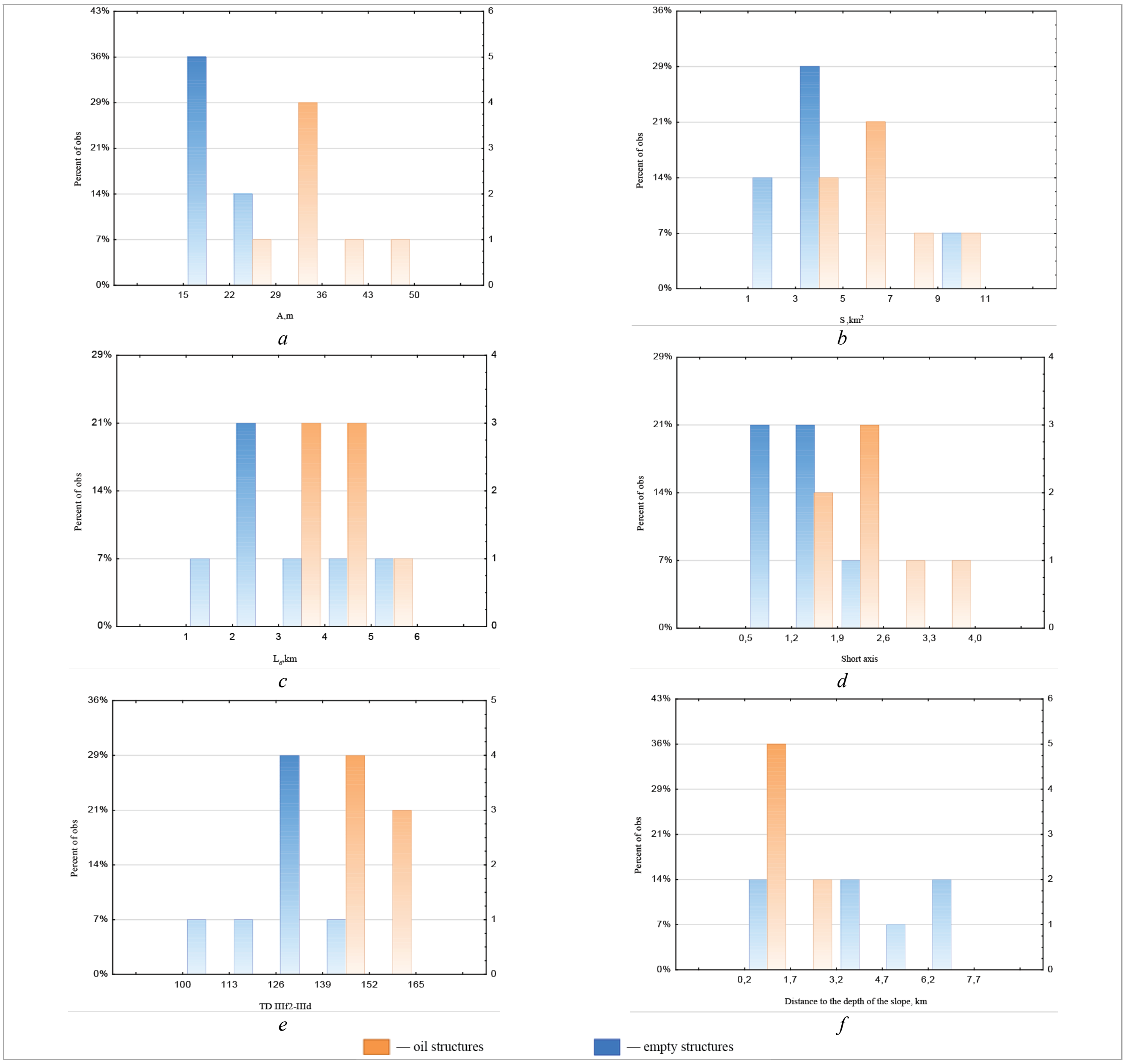

Fig. 2. Histograms of indicators by categories of oil and empty structures: *a* – amplitude; *b* – area; *c* – is the size of the long axis; *d* – is the size of the short axis; *e* – is the thickness of the Domanic deposits; *f* – distance from the deep-water slope

Table 2

Conditional interval probabilities

A, m	$P(A)$, decimal units	S, km^2	$P(S)$, decimal units	L_d, km	$P(L_d)$, decimal units
15–22	0	1–3	0	1–2	0
22–29	0.33	3–5	0.33	2–3	0
29–36	1	5–7	1	3–4	0.75
36–43	1	7–9	1	4–5	0.75
43–50	*1*	9–11	0.5	5–6	0.5
L_k, km	$P(L_k)$, decimal units	H_{dm}, m	$P(H_{dm})$, decimal units	L_{gs}, km	$P(L_{gs})$, decimal units
0.5–1.2	0	100–113	0	0.2–1.7	0.71
1.2–1.9	0.4	113–126	0	1.7–3.2	1
1.9–2.6	0.75	126–139	0	3.2–4.7	0
2.6–3.3	1	139–152	0.8	4.7–6.2	0
3.3–4	1	152–165	1	6.2–7.7	0

Table 3

Probabilistic models

Parameter	Equation of the probabilistic model	Application Range	Probability range, decimal units
A, m	$P(A) = –0.3722 + 0.0267·A$	15–50	0.0283–0.9628
S, km^2	$P(S) = 0.065 + 0.0835·S$	1–11	0.1485–0.9835
L_d, km	$P(L_d = –0.1575 + 0.165·L_д$	1–6	0.0075–0.8325
L_k, km	$P(L_к) = –0.1107 + 0.2714·L_к$	0.5–4	0.025–0.9749
H_{dm}, m	$P(H_{dm}) = –1.4165 + 0.0146·H_{dm}$	100–165	0.0044–0.9925
L_{gs}, kmм	$P(L_{gs}) = 0.9749 – 0.1147·L_{гс}$	0.2–7.7	0.092–0.952

Table 4

Individual and complex probabilities of oil and gas bearing capacity

Structure	Class	$P(A)$, decimal units	$P(S)$, decimal units	$P(L_d)$, decimal units	$P(L_k)$, decimal units	$P(H_{dm})$, decimal units	$P(L_{gs})$, decimal units	P_{comp} decimal units
Y.-Sedemesskaya	oil	0.429	0.953	0.705	0.473	0.657	0.889	0.998
Demaelian	oil	0.429	0.652	0.451	0.552	0.628	0.820	0.916
Bedamelskaya	empty	0.215	0.733	0.668	0.408	0.511	0.459	0.479
Yu.-Pychskaya	empty	0.028	0.324	0.291	0.275	0.540	0.183	0.001
S.-Bolotnaya	empty	0.162	0.150	0.083	0.104	0.759	0.854	0.007
Shcheliayurskaya	oil	0.749	0.498	0.514	0.704	0.847	0.751	0.992
V.-Schelyayurskaya	empty	0.162	0.407	0.494	0.212	0.613	0.086	0.005
S.-Volminskaya	empty	0.322	0.458	0.626	0.402	0.058	0.872	0.160
Strelinskaya	empty	0.189	0.399	0.338	0.345	0.321	0.269	0.007
V.-Volminskoye	oil	0.295	0.574	0.453	0.432	0.963	0.929	0.992
Makaryelskaya	oil	0.963	0.580	0.585	0.351	0.920	0.946	1.000
Nizevaaya	oil	0.429	0.331	0.352	0.324	0.642	0.659	0.251
Yu.-Nizevaya	oil	0.482	0.393	0.569	0.866	0.657	0.809	0.977
S.-Osinovaya	empty	0.028	0.211	0.255	0.115	0.438	0.459	0.000
Pilegorskaya	–	0.349	0.900	0.998	0.975	0.584	0.356	0.98
V.-Makaryelskaya	–	0.242	0.376	0.569	0.215	0.336	0.946	0.381
Voskresenskaya	–	0.242	0.297	0.272	0.296	0.409	0.843	0.073

According to the histogram of amplitudes (see Fig. 2, *a*), it was found that the most common amplitude values for oil structures are in the range of 29–36 m (29 %), for empty structures – 15–22 m (36 %). The overlapping zone of the classes is determined in the interval of 22–29 m. Amplitude of more than 29 m is typical only for oil structures.

The most common area values (see Fig. 2, *b*) for oil structures are in the range of 5–7 km2 (27 %), for empty structures – 3–5 m (29 %). Basically, empty structures are characterized by a smaller area value compared to the oil-saturated ones.

From the histogram of the dimensions of the long axes of the structures (see Fig. 2, *c*) it can be seen that the most common values for oil structures are in the range of 3–5 km (42 %), for empty structures – 2–3 km (21 %). The overlapping zone of categories is determined in the interval of 3–6 km. It is worth noting that if the value of this parameter is less than 3 km, only empty structures are found.

The most common values of short axis lengths (see Fig. 2, *b*) for oil structures are in the range of 1.9–2.6 km (21 %), for empty structures – 0.5–1.9 m (42 %). The overlapping zone of classes is 1.2–2.6 km.

The most common values of Domanic horizon thickness (see Fig. 2, *e*) for oil structures are in the range of 139–152 m (29 %), for empty structures – 126–139 m (29 %). The overlapping zone of the categories is determined in the interval of 139-152 m.

With thicknesses less than 139 m, only empty structures are found.

According to the histogram of distance from the deep-water slope (see Fig. 2, *f*), it was established that oil structures occur at values of this parameter less than 3.2 km, empty structures are found at the entire range of values of 0.2–7.7 km.

In the next step, for each interval highlighted in the histograms, the details are determined according to the formula:

$$P\left(X_j | W_k\right) = \frac{N_k}{N_q}, \qquad (1)$$

where $P\left(X_j | W_k\right)$ – specific value in the *k-th* interval for the group *Wq* (*q* = 1 – corresponds to oil structures, and *q* = 2 – empty structures); *Nk* - number of cases of parameter *Xj* content in the *k-th* interval; *Nq* - sample volume of structures with this or that character of saturation.

The calculated specifics were used to calculate conditional interval probabilities of oil and gas content:

$$P\left(W_q|X_j\right)_k = \frac{P\left(X_j|W_1\right)_k}{P\left(X_j|W_1\right)_k + P\left(X_j|W_2\right)_k}, \quad (2)$$

where $P\left(W_q|X_j\right)_k$ – is the conditional interval probability that variable *Xj* in the *k-th* interval belongs to class *Wq*. Conditional interval probabilities for each parameter are presented in Table 2.

Linear probabilistic models of oil-and-gas bearing capacity of the structures for each parameter are constructed by the obtained data. The methods of construction of probabilistic models for oil and gas content prediction are given in [42]. The obtained model equations and the limitations of their use are presented in Table 3.

The equations of probability models show that the probability of oil and gas bearing is characterized by a direct dependence on the amplitude, area of the structure, the size of the long and short axes, and the thickness of the domanic sediments, and by an inverse dependence – with the distance from the deep-water slope. It is also important to note that the obtained probabilistic models are correct: the range of probabilities is from 0 to 1 decimal units and all models cross the line with a probability of 0.5 decimal units.

Complex model construction

When predicting oil and gas potential, it is necessary to take into account all considered indicators in aggregate. To do this, the study calculates a complex indicator, the use of which is described in the works [43]. The complex probability was calculated by the formula:

$$P_{comp} = \frac{\prod_{j=1}^{m} P(W_н \mid X_j)}{\prod_{j=1}^{m} P(W_н \mid X_j) + \prod_{j=1}^{m}(1 - P(W_н \mid X_j))}, \quad (3)$$

Table 4 shows the values of conditional probabilities for each parameter, as well as the complex probability of oil and gas content of the reference and prepared structures.

A histogram of complex probabilities for classes of oil-saturated and empty structures (Fig. 3) was constructed to verify the obtained probabilistic statistical model.

Figure 3 and Table 4 show that all oil structures are characterized by a complex probability of more than 0.5 decimal units. For all empty structures, the probability of oil content is less than 0.5 decimal units, with the majority in the range of 0-0.1 decimal units.

Another method of testing the obtained model is to compare the complex probability of oil and gas potential identified in the course of the probabilistic-statistical analysis of Rcomp with the probability and gas potential according to the results of the discriminant analysis of Rcomp (discr). The possibilities of using discriminant analysis to solve predictive problems are given in [44, 45]. To compare the obtained probabilities, a correlation field is constructed (Fig. 4).

According to the correlation field, it was identifyied that the structures were divided into two groups: oil-saturated with complex probabilities for both types of

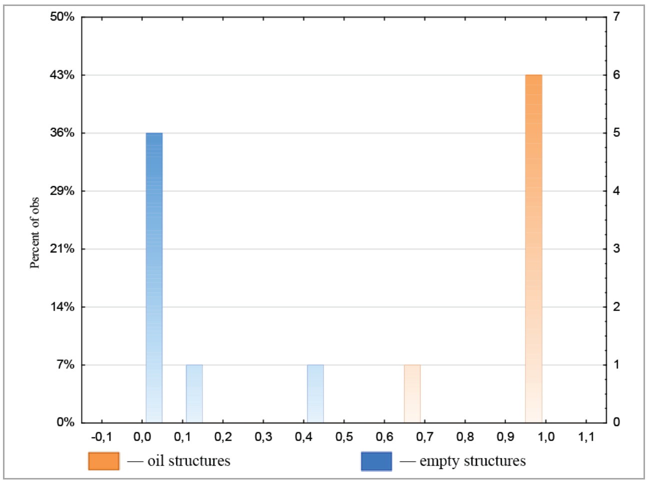

Fig. 3. Histogram of complex probabilities by categories

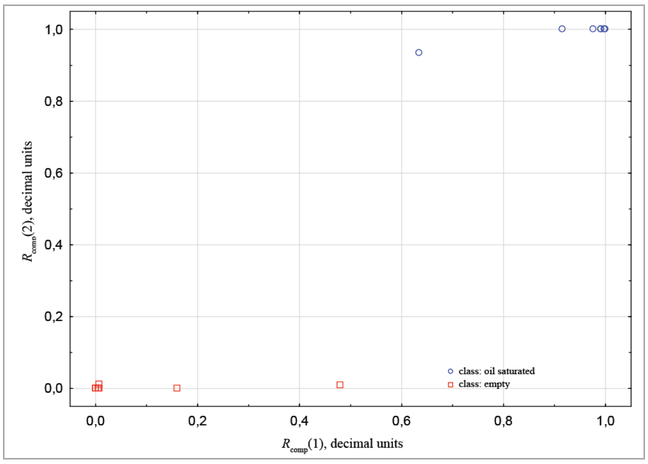

Fig. 4. Correlation field of R_{comp} (1) and R_{comp} (2) (discr)

analysis greater than 0.5 decimal units and empty – with probabilities less than 0.5 decimal units. Thus, the obtained probabilistic-statistical model is acceptable for ranking structures by prospects of oil and gas bearing capacity.

Conclusion

The Pilegorskaya structure has the highest probability of oil bearing capacity of 0.98 decimal unit. The prospectivity of drilling this structure is also confirmed by the fact that this structure has the largest amount of prepared resources among all the structures under consideration, which is one of the significant factors in selecting the first-priority object.

According to the analysis results, the East Makaryelskaya structure has a complex probability of 0.381 decimal units, which is below the boundary value. Voskresenskaya structure has the lowest complex probability of all the structures considered, which indicates that prospecting and appraisal works there are not promising.

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