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Application of Dispersed Organic Matter Characteristics of Rocks for Zonal Prediction of Oil and Gas Potential on the Northern Part of the Baskir Arch

Polina O. Chalova

Perm National Research Polytechnic University (29 Komsomolskiy av., Perm, 614990, Russian Federation)

Применение характеристик рассеянного органического вещества пород для зонального прогноза нефтегазоносности северной части Башкирского свода

П.О. Чалова

Пермский национальный исследовательский политехнический университет
(Российская Федерация, 614990, г. Пермь, Комсомольский проспект, 29)

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Keywords:
Bashkir arch, dispersed organic matter, statistical evaluation, bitumen coefficient, epigenetic bitumoids, complex geochemical criterion, oil and gas potential.

The article is based on the example of the northern part of the Bashkir arch to make a zonal prediction of oil and gas potential based on the characteristics of dispersed organic matter (DOM). For this purpose, at the first stage of the study, the DOM was classified into types: syngenetic and epigenetic using various statistical methods. All this made it possible to construct individual and complex probability models for predicting epigenetic (the most migratory) dispersed organic matter. It was found that high values of complex probability correlate with discovered hydrocarbon deposits. This confirms the migration ability of bitumoids with the subsequent formation of commercial hydrocarbon deposits. Probabilistic DOM indicators that determine the complex probability of epigenetic DOM reliably control the oil and gas potential of sediments. The values of bitumen coefficient and insoluble residue have the maximum influence on the value of complex probability and on the differentiation of DOM. The insoluble residue has a high holding capacity and almost completely controls the process of differentiation of the organic matter up to the value of the complex probability equal to 0.55-0.6, then, as the complex probability increases, the influence of the insoluble residue weakens. The bitumen coefficient, in this case, affects the DOM differentiation in the whole range of complex probability change.

Ключевые слова:
Башкирский свод, рассеянное органическое вещество, статистическая оценка, битумоидный коэффициент, эпигенетические битумоиды, комплексный геохимический критерий, нефтегазоносность.

На примере северной части Башкирского свода выполнен зональный прогноз нефтегазоносности по характеристикам рассеянного органического вещества (РОВ). Для этого на первом этапе исследования осуществлена типизация РОВ по типам: сингенетичное и эпигенетичное с помощью различных статистических методов. Все это позволило построить индивидуальные и комплексную вероятностные модели прогноза эпигенетичного (наиболее миграционно способного) рассеянного органического вещества. Установлено, что высокие значения комплексной вероятности коррелируют с открытыми месторождениями углеводородов. Это подтверждает миграционную способность битумоидов с последующим образованием промышленных залежей углеводородов. Вероятностные показатели РОВ, определяющие комплексную вероятность эпигенетического РОВ, надежно контролируют нефтегазоносность отложений. Максимальное влияние на величину комплексной вероятности и на дифференциацию РОВ оказывают величины битумоидного коэффициента и нерастворимого остатка. Нерастворимый остаток обладает большой удерживающей способностью и практически полностью контролирует процесс дифференциации РОВ до величины комплексной вероятности, равной 0,55–0,6 доли ед., далее, по мере увеличения комплексной вероятности, влияние нерастворимого остатка ослабевает. Битумоидный коэффициент при этом оказывает влияние на дифференциацию РОВ во всем диапазоне изменения комплексной вероятности.

© **Polina O. Chalova** (Author ID in Scopus: 57223986143, ORCID: 0000-0002-4862-0116) – Assistant at the Department of Oil and Gas Geology (tel.: +007 (922) 305 75 15, e-mail: chalovapolina@yandex.ru).

© **Чалова Полина Олеговна** – ассистент кафедры «Геология нефти и газа» (тел.: +007 (922) 305 75 15, e-mail: chalovapolina@yandex.ru).

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Introduction

Organic matter dispersed in sedimentary rocks provides valuable information about the oil and gas potential of the sedimentary strata. Analysis of the component composition of dispersed organic matter (DOM) allows us to determine the nature, accumulation conditions and maturity of DOM, as well as to assess the generation potential of sediments and use it to forecast the oil and gas potential of the territory [1–4]. Many researches have been devoted to the study of the elemental composition of DOM during catagenesis, the most significant of which are the works of V.A. Uspensky, N.B. Vassoevich, S.G. Neruchev, O.A. Radchenko, A.E. Kontorovich, G.A. Kalmikov and others [5–9]. Today, there are many methods for studying the composition of dispersed organic matter [10, 11], the most frequently used include: chemical-bituminological analysis, pyrolysis using the Rock-Eval method, gas-liquid chromatography, etc.

The characteristics of DOM are directly related to the oil and gas potential [12–14]. The basis of bituminological analysis is the sequential extraction of bitumoids using organic solvents (chloroform, benzene, petroleum ether, etc.) and alkali for the subsequent isolation of humic acids, which are a part of the residual organic matter. Further extraction is accompanied by elemental analysis, analysis of the group hydrocarbon composition, as well as carbon petrographic study of the insoluble residue [15–18].

The Rock-Eval method, which involves the pyrolysis of a rock core in an inert atmosphere using a Rock-Eval instrument, is an integral part of oil and gas potential forecast worldwide. It was developed for detailed analysis of source rocks [19]. The results of Rock-Eval analysis are applicable to both new prospective oil and gas regions and highly studied areas for supplementary exploration purposes [20]. The advantages of the Rock-Eval method include relatively short analysis time, minimal sample preparation, and small sample weight [21–24]. In this method, a programmable temperature heating of a small amount of rock (70 mg) or coal (30–50 mg) is carried out in an inert atmosphere (helium or nitrogen) to determine the amount of free hydrocarbons present in the sample, which characterizes the proportion of the original genetic material transformed into hydrocarbons ($S1$), and those that can potentially be released after maturation, which characterizes the residual petroleum potential ($S2$). Based on the results of determining $S1$ and $S2$, standardized T_{max} values and productivity index (PI) (the ratio of $S1/(S1+S2)$) are calculated. These criteria are used as parameters that characterize the maturity of fossil organic matter. For a more complete rock testing, the total organic content (TOC) and mineral carbon content (MinC) are also determined.

The gas-liquid chromatography method allows for the analysis of the complex mixture composition of organic compounds, including the methane-naphthenic hydrocarbon fraction of bitumoids and oil, consisting of saturated high-molecular hydrocarbons. This method is characterized by fast analysis time, clarity, the ability to work with small samples [25, 26] and is often used in addition to the first two methods to compare the migration part and the source rock, oil and the source rock [27].

Compared to bituminological analysis, physical processes are studied in the process of rock pyrolysis, while the first method allows studying the chemical composition of bitumoids, which is of great interest in analyzing the process of generation, accumulation and migration of dispersed organic matter. In addition, another distinctive feature of bituminological analysis is the large volume of research conducted. Studies using Rock-Eval method and gas-liquid chromatography are carried out in single wells in the Perm Krai, therefore, it is not possible to assess the differentiation of DOM by section and area based on the results of these studies.

In this regard, we present data from bituminological analysis, according to which syngenetic host deposits and epigenetic bitumoids are distinguished [28]. The amount of epigenetic bitumoids in rocks is of the greatest interest since they are more mobile, migration-capable, and are equivalent to micro-oil.

The division of DOM into types is based on the Uspensky-Vassoevich law, according to which the proportion of bituminous components in it increases with the dispersion of organic matter [29–31]. To support and further prove this classification, scientists have developed a methodology for dividing DOM into three classes (syngenetic, epigenetic and mixed) using probabilistic-statistical methods, which have been increasingly used in the oil and gas industry over the past decade [32–36].

The aim of this study is to assess the differentiation of DOM using probabilistic-statistical methods based on bituminological analysis data from the northern part of the Bashkir arch to make further zonal forecast of oil and gas potential.

Object of study

The object of the study is the sedimentary strata of the southern part of the Bashkir Arch within the Perm Krai. The Bashkir Arch (BA), in turn, is a first-order positive tectonic structure, that acquired its modern outlines at the end of the Hercynian geological cycle [37, 38]. The arch is complicated by numerous second-order structures – ridges and third-order structures – local uplifts. In geological terms, the BA is located in the eastern edge of the East European Platform. Within the study object, as of January 1, 2024, 56 fields are being developed, 9 fields are under exploration, 12 structures are in deep drilling, 34 are prepared for deep drilling, and 40 have been identified. The BA is noted for its industrial oil-bearing capacity in all oil and gas-bearing complexes characteristic of the Volga-Ural oil and gas-bearing province. However, despite its high level of exploration, the oil and gas potential forecast for this area remains relevant.

Construction of probabilistic-statistical models of zonal oil and gas potential forecast based on the characteristics of DOM

Geochemical characteristics of DOM within the study area were analyzed using the bituminological method in 62 wells, in total 1617 core samples were analyzed. The following key parameters were considered: content of organic matter (OM, %) and organic carbon (C_{org}, %); composition of DOM – percentage content of chloroform (B_{cl}), petroleum (B_{pe}), alcohol-benzene (B_{ab}) bitumens, content of humic acids (HumA, %) and insoluble residue (IR, %); characteristic of DOM transformation – bitumen neutrality coefficient ($K_n = B_{cl}/B_{ab}$, fr. of units), bitumen coefficient (β, %).

Differentiation of DOM by types was carried out using statistical analysis according to the technology described in [33]. The correlation field between C_{org} and β according to the available data is presented in Fig. 1.

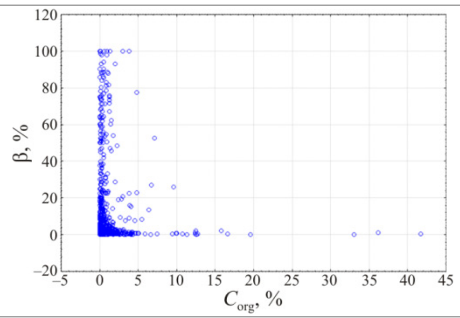

Fig. 1. Correlation field between the C_{org} and β parameters for the territory of the Bashkir arch

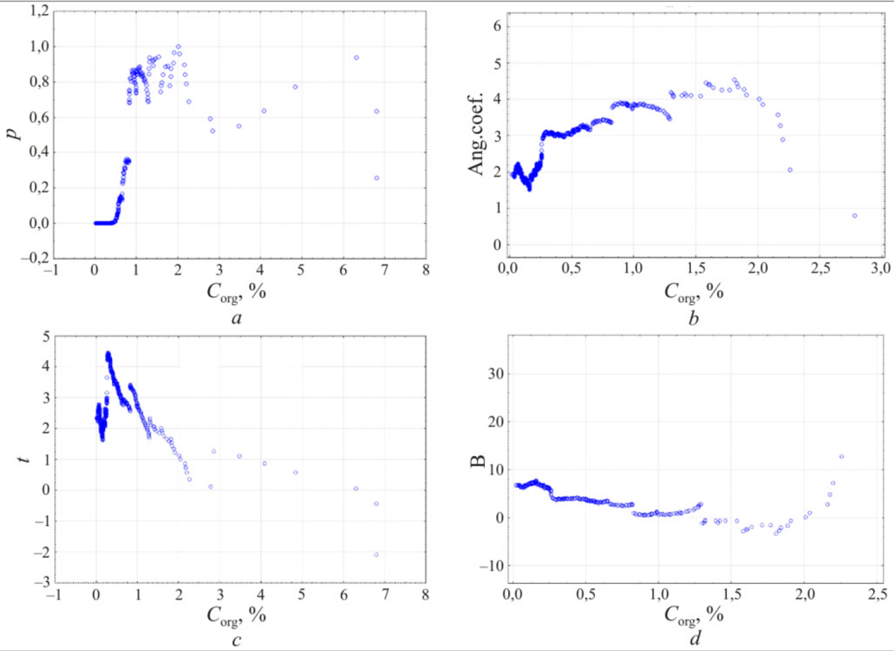

Fig. 2. Change in values: *a* – significance level; *b* – angular coefficient; *c* – *t*-criterion; *d* – free term in the regression equations $\beta = f(C_{org})$

The relationship between the geochemical characteristics C_{org} and β is characterized by significant non-linearity. The observed pattern of changes in β values with respect to C_{org} suggests that the process of DOM transformation proceeds according to a general scheme [39]. The intensity of the transformation process is determined by different values of C_{org} concentrations. Therefore, it is advisable to conduct a study of the relationship nature between β and C_{org} in order to determine the range of C_{org} values with a statistically significant inverse correlation with the coefficient β, which will be the boundary value of DOM differentiation into autochthonous and allochthonous type.

Thus, to classify DOM types in the studied territory of the BA, the results of sample analysis with both C_{org} and β determined jointly, were used. Linear regression equations were constructed for different ranges of C_{org} to differentiate the relationship between β and C_{org}. The first model is constructed using 3 (n = 3) determinations of C_{org}, the next model was obtained with n = 4, and so on up to n = 711. In total, 708 statistical models were constructed.

The characteristics of the statistical models were used to construct relationships between the changes in the free terms, coefficients of C_{org}, and correlation coefficients r as a function of C_{org} values (Fig. 2).

Analysis of the obtained relationships based on the model characteristics allowed for the identification of three groups. Discriminant analysis was performed on these three groups to determine functions that could separate the classes. To construct a linear discriminant function, matrices of centered sums of squares and mixed products were created, from which sample matrices were calculated [40-42]. The following linear discriminant functions (LDF) were constructed:

$$Z1 = 0{,}10051 \cdot \beta - 0{,}0039 \cdot \mathrm{IR} - 0{,}93401 \cdot B_{cl} + $$
$$+ 1{,}738 \cdot B_{ab} + 0{,}178 \cdot K_n - 1{,}5923,$$
$$\chi^2 = 1384{,}204;\ p = 0{,}0000000$$

$$Z2 = -0{,}02731 \cdot \beta - 0{,}01173 \cdot \mathrm{IR} - 2{,}2294 \cdot B_{cl} + $$
$$+ 5{,}6051 \cdot B_{ab} + 0{,}7246 \cdot K_n - 0{,}0658 \cdot \mathrm{OB} + 0{,}2291,$$
$$\chi^2 = 59{,}118;\ p = 0{,}0000000.$$

The obtained functions are statistically significant, as confirmed by the level of significance of the obtained relationships and the values of χ^2. The accuracy of classification on the training sample is 92.21 %. Differentiation of the DOM by type occurs to a greater extent according to the $Z1$ function.

The analysis of the obtained LDF shows that the order of formation occurs in the sequence of the parameter arrangement in the equation. At the first step, the β parameter is included, then the IR value, and so on. Thus, the differentiation obtained by the C_{org} and β parameters is also observed in other geochemical characteristics of DOM. All this allows us to justify the differentiation of DOM into three classes at the statistical level.

Comparison of average values of DOM parameters by types

Parameters, fr.of units	Average values			Criteria
	Type of DOM			$\frac{t}{p}$
	syngenetic	mixed	epigenetic	
IR, %	60.875 ± 39.117		16.634 ± 29.951	12.224 / 0.000
	60.875 ± 39.117	30.036 ± 35.065		5.316 / 0.000
		30.036 ± 35.065	16.634 ± 29.951	2.561 / 0.011
C_{org}, %	1.487 ± 3.505		0.680 ± 1.287	2.667 / 0.008
	1.487 ± 3.505	0.830 ± 1.199		1.319 / 1.188
		0.830 ± 1.199	0.680 ± 1.287	0.718 / 0.474
OM, %	1.974 ± 4.662		0.907 ± 1.713	2.651 / 0.008
	1.974 ± 4.662	1.102 ± 1.595		1.314 / 0.189
		1.102 ± 1.595	0.907 ± 1.713	0.705 / 0.482
B_{pe}	0.002 ± 0.011		0.077 ± 0.124	-13.499 / 0.000
	0.002 ± 0.011	0.022 ± 0.046		-7.802 / 0.000
		0.022 ± 0.046	0.077 ± 0.124	-3.019 / 0.003
B_{cl}	0.035 ± 0.078		0.605 ± 1.075	-12.014 / 0.000
	0.035 ± 0.078	0.222 ± 0.317		-10.594 / 0.000
		0.222 ± 0.317	0.605 ± 1.075	-2.475 / 0.014
B_{ab}	0.079 ± 0.100		0.281 ± 0.412	-10.057 / 0.000
	0.079 ± 0.100	0.311 ± 0.407		-10.191 / 0.000
		0.311 ± 0.407	0.281 ± 0.412	0.446 / 0.656
HumA %	0.012 ± 0.039		0.001 ± 0.002	3.156 / 0.002
	0.012 ± 0.039	0.001 ± 0.001		1.897 / 0.058
		0.001 ± 0.001	0.001 ± 0.002	-0.040 / 0.968
K_n, fr. of units	0.366 ± 0.277		1.878 ± 2.370	-14.114 / 0.000
	0.366 ± 0.277	0.774 ± 0.408		-9.383 / 0.000
		0.774 ± 0.408	1.878 ± 2.370	-3.237 / 0.001
β, %	3.147 ± 3.254		61.358 ± 21.851	-58.589 / 0.000
	3.147 ± 3.254	19.389 ± 3.265		-33.702 / 0.000
		19.389 ± 3.265	61.358 ± 21.851	-13.505 / 0.000

The classes identified by statistical analysis are associated with syngenetic, mixed and epigenetic types of DOM. The Uspensky-Vassoevich law adjusted for statistically substantiated types of DOM for the BA territory, is presented graphically in Fig. 3.

The differentiation of DOM is observed strongly by β rather than by C_{org}. It has been established that the existence of mixed and epigenetic DOM is observed only at C_{org} values of < 10 %. This circumstance shows that the process of DOM transformation occurs in sediments where the C_{org} concentration value is less than 10 %. The boundary between syngenetic and mixed DOM fluctuates by the β parameter in the range of 15–18 %. The boundary between mixed and epigenetic DOM is at the β value of 28–32%. The distribution by the number of determinations is as follows: 73.45 % – syngenetic DOM; 8.65 % – mixed, and 17.89 % – epigenetic.

To confirm that the identified DOM groups are characterized by different average values of the studied characteristics, an analysis was performed using the Student's t-test [43, 44]. The difference in average values by DOM types is considered statistically significant if the t-criterion value is different from 0, and the significance level p is less than or equal to 0.05. Average values of geochemical parameters for the identified DOM types, t and p statistics are given in the table.

Analysis of the calculated average values of the main geochemical characteristics of DOM shows a statistically different composition of syngenetic, mixed and epigenetic bitumoids.

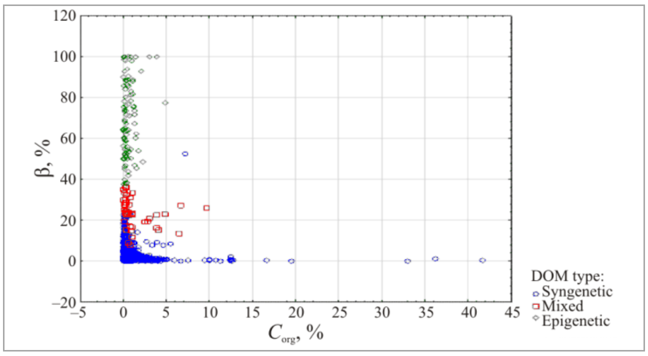

Fig. 3. Correlation field between C_{org} and β with selected DOM groups for the BA territory

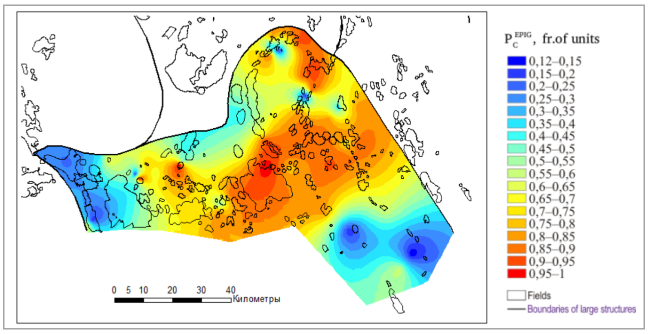

Fig. 4. Scheme of changing P_C^{EPIG} values across the territory of the northern part of the Bashkir arch

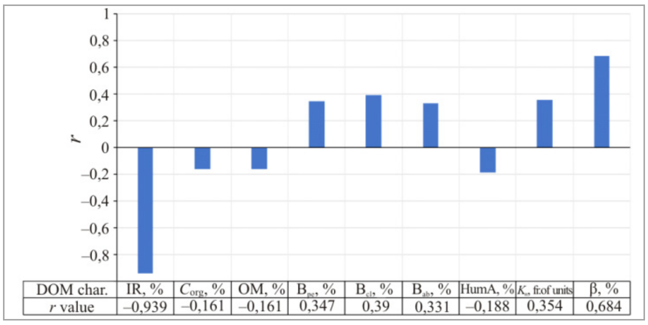

Fig. 5. Values of the correlation coefficients (r) between the characteristics of the DOM and P_C^{EPIG}

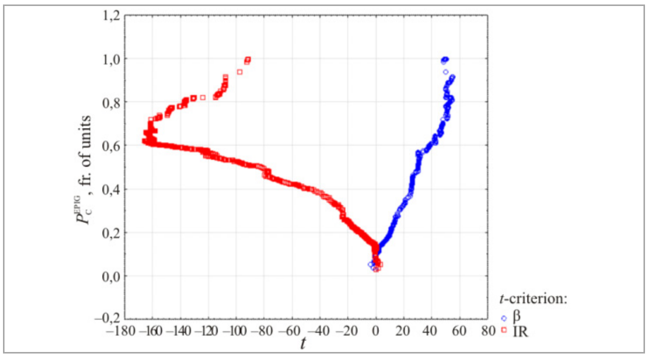

Fig. 6. Change in the values of the t-criterion coefficients in the equations $P_C^{EPIG} = f(\beta,\ \mathrm{IR})$

The maximum difference in average values for all parameters was obtained between the characteristics of syngenetic and epigenetic DOM. This also proves that differentiation of DOM is observed not only by the ratio of β and C_{org}, but also by other characteristics of OM. For the forecast of oil and gas potential, it is important to assess the differentiation and typing of DOM by the degree of prevalence of epigenetic (most mobile) bitumoids.

Thus, the differentiation of DOM obtained by the content of organic carbon C_{org}, %, and the bitumen coefficient β, %, was used to construct probabilistic models for forecasting the presence of epigenetic DOM in the BA territory. The algorithm for constructing individual and complex models is also presented in [45, 46]. It is also worth noting that two types of bitumoids were used to construct the models – syngenetic and epigenetic. A total of 9 individual probability models were constructed for all the studied DOM characteristics. Further, a complex criterion for forecasting epigenetic DOM has been developed for individual probabilistic models – P_C^{EPIG}, determined by the following formula:

$$P_C^{EPIG} = \frac{\prod Pepig\,i}{\prod Pepig\,i + \prod\left(1 - Pepig\,i\right)},$$

where $Pepig\,i$ – respectively, individual probabilities: P(IR), P(β), P(C_{org}), P(OM), P(B_{PE}), P(B_{Cl}), P(B_{AB}), P(HumA), P(B_{Cl} / B_{AB}).

The change in the complex probability of the manifestation of epigenetic bitumen on the BA territory is graphically presented in Fig. 4.

Analysis of the constructed scheme of changing values P_C^{EPIG} showed that the values P_C^{EPIG} > 0.5 correlates to a greater extent with discovered fields, indicating the migration capacity of bitumoids and, as a result, the formation of industrial accumulations of hydrocarbons. Probabilistic parameters of DOM, which make up the complex probability P_C^{EPIG}, control the oil and gas content of deposits. Correlation links between P_C^{EPIG} and the values of the studied characteristics of DOM are shown in Fig. 5.

The characteristics of IR, %, and β, % have the strongest correlation with the value of the complex probability. Therefore, it is advisable to analyze the joint influence of the β and IR characteristics on the value P_C^{EPIG}, fr. of units, throughout the sedimentary thickness of the BA.

The joint influence of the characteristics was assessed using the construction of multiple regression equations and the analysis of the t-criterion of the coefficients for the dependent variables β and IR; the results of the construction are presented graphically in Fig. 6.

According to Fig. 4, the ranges of variation in the t-criterion values for the bitumoid coefficient and the insoluble residue are different. The range of variation in the t-criterion for the β coefficient is from –7 to 50, while the t-criterion itself steadily increases over the entire range of variation in the complex probability. The t-criterion for the IR coefficient varies over a much larger range, up to the value P_C^{EPIG} equal to 0.6 fr. of units, the t-criterion increases steadily, indicating its greater retention capacity. Further, in the complex probability increases, the influence model changes, and the t-criterion value decreases, and indicating an increase in the mobility of DOM.

Conclusion

The study of the C_{org} and β ratio, using regression and discriminant analysis made it possible to substantiate the differentiation of DOM by types (syngenetic, mixed and epigenetic) in the BA territory. The reliability of typing is confirmed by the χ^2 value and a high percentage of classification accuracy. Comparison of the average values of the characteristics for the identified types using the t-criterion also confirmed the correctness of the identified DOM types.

The constructed individual probability models based on the characteristics of DOM allowed us to develop a complex probabilistic-statistical model for forecasting the epigenetic DOM.

A diagram was constructed based on the values of the complex probability for the BA. The values $P_К^{ЭПИ} > 0.5$ fr. of units correlate with discovered deposits, indicating the migration capacity of bitumoids with the subsequent formation of industrial hydrocarbon deposits. Probabilistic parameters of the DOM that make up the complex probability P_C^{EPIG}, control the oil and gas content of deposits.

It has been established that the characteristics with the greatest influence on the value P_C^{EPIG} are the bitumoid coefficient β, %, and the value of the insoluble residue IR, %.

A detailed statistical analysis of the influence of β, %, and IR, %, on the value of the complex probability showed that as the complex probability increases, the *t*-criterion value for the bitumen coefficient steadily increases. The IR, % parameter has a large retaining capacity and controls the process of DOM differentiation up to the complex probability value equal to 0.55–0.6 fr. of a unit, and then, as the complex probability increases, the value of the insoluble residue has a less effect on the process of DOM differentiation.

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