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Development of a Complex Geochemical Criterion that Determines the Distribution of the Total Oil and Gas Content of the Solikamsk Depression section

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Разработка комплексного геохимического критерия определяющего распределение суммарной нефтегазоносности разреза Соликамской депрессии

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oil and gas potential forecast, oil and gas bearing complex, probabilistic-statistical models, probability, Solikamsk depression, Perm Krai, Kama-Kinel trough system, dispersed organic matter, geochemical indicators, domanik facies, bitumen coefficient β, complex criterion.

The results of a probabilistic-statistical assessment of the geochemical characteristics of the section of the main oil and gas source strata of the Solikamsk depression and their relationship with the total oil and gas content of the section are presented. For comprehensive accounting and identification of the optimal combination of geochemical parameters that determine the oil and gas content distribution, a complex probabilistic criterion has been developed for each oil and gas complex – R_{comp}. Statistical analysis confirmed that the Upper Devonian-Tournaisian deposits in most of the Solikamsk Depression territory were in the main phase of oil formation, and there the maximum mobile bitumen formation occurred, including hydrocarbons, which took an active part in the total oil and gas content formation of the Solikamsk Depression. A fundamentally different nature of changes in the values of the developed complex geochemical criterion has been established in depth for wells located within the oil and gas bearing contours and beyond them. The most informative criterion indicating the relationship between DOM and the total oil and gas content of a section is the bitumen coefficient β.

Ключевые слова:
прогноз нефтегазоносности, нефтегазоносный комплекс (НГК) вероятностно-статистические модели, вероятность, Соликамская депрессия (СолД), Пермский край, Камско-Кинельская система прогибов (ККСП), рассеянное органическое вещество (РОВ), геохимические показатели, доманиковые фации, битумоидный коэффициент β, комплексный критерий ($P_{комп}$).

Приведены результаты вероятностно-статистической оценки геохимических характеристик разреза основных нефтегазоматеринских толщ Соликамской депрессии и их связь с суммарной нефтегазоносностью разреза. Для комплексного учета и выявления оптимального сочетания геохимических параметров, определяющих распределение нефтегазоносности, разработан комплексный вероятностный критерий для каждого НГК – $P_{комп}$. Статистическим анализом подтверждено, что отложения верхнедевонско-турнейского комплекса на большей части территории Соликамской депрессии находились в главной фазе нефтеобразования, и там происходило максимальное образование подвижных битумоидов, включая углеводороды, которые приняли активное участие в формировании суммарной нефтегазоносности разреза Соликамской депрессии. Установлен принципиально различный характер изменения значений разработанного комплексного геохимического критерия – $P_{комп}$ – по глубине для скважин, находящихся в контурах нефтегазоносности и за их пределами. Наиболее информативным критерием, указывающим на связь РОВ с суммарной нефтегазоносностью разреза, является битумоидный коэффициент β.

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Introduction

At the end of the last century, it was established that an oil and gas bearing basin had all the main features of self-developing systems, and therefore the mathematical tools could be successfully used in further development of oil and gas formation theory [1].

Research analysis allows making geological conclusions based on mathematical analysis, which can be found in works of many Russian and foreign authors [2–32].

As a part of the research, a probabilistic-statistical analysis of the systematised geochemical characteristics of the dispersed organic matter found in the main oil and gas source strata was performed. In order to carry out statistical calculations, classes were identified among the objects, dividing them into objects located within the field limits and in areas with no oil and gas content. Linear and multidimensional probability models were constructed on geochemical parameters, and the effects of each parameter in the aggregate and separately were studied.

According to the oil and gas geological zoning of Perm Krai, the Solikamsk Depression (SolD) refers to the oil and gas bearing area of the same name in the Kama-Kinel oil and gas bearing area [33]. As to the map of JSC "KamNIIKIGS" the territory is included to the Solikamsk oil-and-gas bearing area of the Middle-Preduralskaya petroleum area [34]. A wide range of articles [35-42] is devoted to the studies of oil and gas content of the area.

549 wells were drilled on the depression, the density of deep drilling is 104.59 m/km^2.

33 oil fields were discovered on the SolD area by 01.01.2022. Commercial oil deposits, ingress of oil and gas are found in six oil and gas bearing complexes. The distribution of commercial oil deposits in the stratigraphic range of the studied section for the fields of the paleoplateau zone and beyond is shown in Fig. 1.

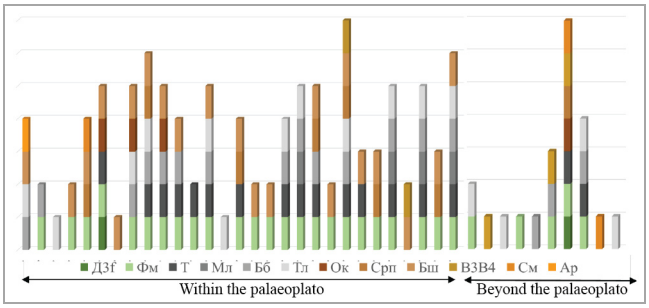

Fig. 1. Commercial oil-and-gas content in the fields of the Solikamsk depression

Exploration of the Solikamsk Depression by Geochemical Studies

Hydrocarbon (HC) generation from dispersed organic matter (DOM) of rocks, migration of micro-oil, its accumulation in natural reservoirs and conservation of formed HC deposits are conditioned by a large number of various parameters and criteria controlling their flow and direction. The oil source formations in the Volga-Ural basin are distinguished in a wide stratigraphic range: from Riphean to Permian sediments. The main oil-producing strata in Perm section are the sediments of the Domanic facies, which are members and formations of thin-layered bituminous rocks with a peculiar fauna. The rocks that form the facies are characterised by an increased bitumen content, up to the formation of combustible shales; most often they are bituminous limestones and shales, as well as siliceous shales and limestones, also bituminous. Mainly Franckian, Famennian and partly Tournaisian sediments developed within the axial zone of the Kama-Kinel oil and gas bearing area belong to the Domanic facies.

The generation potential of oil and gas source strata of the Late Devonian-Tournaisian age is widely covered and estimated on the results of chemical and bituminological, and pyrolytic studies of DOM and bitumoids [43–46].

However, in addition to the main oil and gas source strata, the section also contains source strata of oil-and-gas bearing complexes occurring below and above the section. In order to study geochemical characteristics and DOM parameters of all oil and gas source strata in the SolD section, a geochemical database was formed. To obtain more detailed information on the geochemical parameters distribution, data from wells located in close proximity to the SolD boundaries were analysed.

In total 150 wells were selected for studies, within which 4536 determinations of geochemical characteristics were analysed: percentage of organic carbon content (C_{org}), dispersed organic matter (DOM), concentration of chloroform (B_{CL}), petroleum (B_{PE}), and alcohol-benzene (B_{AB}) bitumoids, their ratios, bitumoid coefficient (β), bitumen neutrality coefficient ($K_н$), insoluble residue (IR), humic acids (HumA), as well as conversion factor (Kk), which takes into account catagenetic transformation of strata when recalculating C_{org} content in DOM.

The section is characterised by an uneven geochemical data study. The largest number of determinations was studied in sediments of the Upper Devonian-Tournaisian complex (D_3–C_1), then in descending order: Upper Visean-Bashkirian (C_1v–C_2b), Visean (C_1v), Middle Carboniferous (C_2vr), Lower-Upper Devonian (D_1–D_3fr1), Lower Permian (P_1), and Middle-Upper Carboniferous (C_3–C_2ks) OGC. The quantity, quality and results of the available standard determinations of geochemical characteristics for oil source rocks refered to the Vendian sediments did not allow us to establish statistically significant mathematical relationship. The formation share of the total oil and gas content of the Solikamsk Depression section was not determined at this stage of research.

Construction of Linear and Multidimensional Models for Oil and Gas Content Forecast and Development of a Complex Criterion based on Geochemical Data

Probabilistic-statistical methods were used to process the information. The research was carried out separately for the classes of wells by facies (within and beyond palaeoplato) and productivity.

The analysis performed at the first level of statistical modelling to determine the presence or absence of connection between the total oil and gas content of the section (data on the section of all wells located in the oil fields limits and beyond them) showed that the mean values of the studied parameters are statistically different for the Kk, IR, B_{PE}, B_{CL}, B_{AB}, B_{CL}/B_{AB} and β values. The maximum difference in the mean values was obtained for β, and the minimum difference was obtained for the DOM value.

The effect of the bitumoid coefficient value is the most informative. In the range of β less than 30 % there is an excess of frequency values for the areas outside the oil fields over frequencies within them. At β in the range of 30–100 % there is, on the contrary, an excess of frequency values within the oil fields areas over the frequencies of the areas outside the oil fields.

To construct individual probabilistic linear models in each interval, the probabilities of belonging to a class of oil fields (P_{int}) were determined. These values were compared with the average interval values of the parameter. A regression equation was constructed from the data and the matching correlation coefficient r was calculated. For the models construction, the essential condition was that the average value for the class of oil fields should be greater than 0.5, and for the area outside – less than 0.5.

As β values increase, the value of $P(\beta)$ increases according to the individual model.

Analysis of the constructed individual models shows that they have different informativeness. Individual informativeness is calculated by differences in the densities of individual probability distributions by Pearson's statistic (χ^2) with 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 – respectively the number of parameter values for oil and gas bearing areas and for non-oil areas; M_1, M_2 – the number of values within the given interval, respectively, for the two classes under study; e – the number of intervals. The criterion is considered statistically different if $\chi^2_p > \chi^2_t$. The values of χ^2_t are determined according to the number of reference objects and the significance level ($\alpha = 0.05$). The calculation data are given in Table 1.

Hence, we can see that the most indicative are the probabilities separated on the basis of bitumoids: ($P(\beta)$, $P(B_{CL}/B_{AB})$, $P(B_{CL})$, $P(B_{AB})$). Statistically insignificant probabilities by the χ^2 criterion are $P(C_{org})$ and P(OM).

Using the constructed linear probability models, the complex parameter was calculated with the following formula:

$$P_{comp} = \frac{\prod P_{in}}{\prod P_{in} + \prod (1 - P_{in})},$$

where P_{ind} are, respectively, individual probabilities from the studied parameters: P(Kk), P(IR), $P(C_{org})$, P(OM), $P(B_{PE})$, $P(B_{CL})$, $P(H_{um}A)$, $P(B_{CL}/B_{AB})$, $P(\beta)$.

For calculating P_{comp}, the combination of probabilities was used, at which the average values of P_{comp} probabilities differ most strongly in the studied classes at equal m value. Where m is the number of parameters included in the model.

It was established that the probability of belonging to the class of areas within or outside the fields according to individual probabilities of geochemical parameters was distributed as following: an increase in the average of P_{comp} values from 0.509 to 0.516 for oil and gas areas and decrease in average of P_{comp} values from 0.487 to 0.456 for the areas outside the oilfields at consecutive summarising of $P(\beta)$, $P(B_{CL}/B_{AB})$, $P(B_{PE})$, $P(B_{CL})$, $P(B_{AB})$, parameters. With additional stepwise use of other characteristics (P(IR), P(Kk), P(HumA), P(OM), $P(C_{org})$), the average values of P_{comp} change insignificantly.

The given combination of linear values of the corresponding probabilities used in determining the of P_{comp} values allows us to obtain new quantitative changes in the effect of developed criteria on P_{comp}, i.e., the relations can territorially estimate the effect of DOM characteristics measured within oil-and-gas-bearing complexes on the total oil-and-gas content of the Solikamsk Depression section [44–46].

Table 1

Statistical characteristics of individual probabilities

Individual probabilities	$\frac{\chi^2_{1-2}}{p_{1-2}}$	Individual probabilities	$\frac{\chi^2_{1-2}}{p_{1-2}}$
P(Kk)	26.84709 / 0.000001	$P(B_{CL})$	58.08900 / 0.000000
P(IR)	32.22807 / 0.000000	$P(B_{AB})$	48.72921 / 0.000000
$P(C_{org})$	0.486233 / 0.784180	$P(H_{um}A)$	20.04272 / 0.000044
P(OM)	0.465061 / 0.792526	$P(B_{CL}/B_{AB})$	103.2786 / 0.000000
$P(B_{AB})$	55.22883 / 0.000000	$P(\beta)$	159.9784 / 0.000000

Table 2

Average P_{comp} values for OGC

OGC	Average probability values		Criterion $\frac{t}{p}$
	Field limit	Outside Field limit	
D1–D3f1	0.416 ± 0.096	0.422 ± 0.092	0.359696 / 0.719406
D3f2–C1t	0.540 ± 0.105	0.497 ± 0.106	7.76113 / 0.000000
C1v	0.513 ± 0.108	0.449 ± 0.108	6.27872 / 0.000000
C1v2–C2b	0.499 ± 0.155	0.439 ± 0.099	6.47757 / 0.000000
C2vr	0.455 ± 0.144	0.414 ± 0.124	2.94712 / 0.003404
C3-C2ks	0.434 ± 0.153	0.403 ± 0.078	1.04241 / 0.300211
P1	0.409 ± 0.114	0.390 ± 0.107	1.23988 / 0.216253

The obtained data prove that bitumoid parameters are the most statistically significant for dividing the areas into those within the fields of the Solikamsk Depression and outside them. Other geochemical characteristics for these zones differ insignificantly. Differentiation of average P_{comp} values from the number of probabilities for oil and gas areas is lower than for the areas outside the oil fields.

Further statistical modelling depending on the total oil-and-gas content of the section for OGC was performed using P_{comp} values calculated by the full set of geochemical characteristics. The results are given in Table 2.

The data in Table 2 show that the average P_{comp} values statistically differ for the following oil and gas bearing complexes: D_3f_2–C_1t, C_1v, C_1v_2–C_2b and C_2vr. It should be noted that P_{comp} values for the areas within the field limits are greater than 0.5, but according to OGC data: D_3f_2–C_1t and C_1v, for the areas outside the field limits, P_{comp} values are less than 0.5. According to the data given in Table 3, the graphs of changes in the average P_{comp} values are constructed by depth of core sampling for wells within the limits of oil and gas content and outside them for OGC (Fig. 2).

The graph shows that for the section of the Solikamsk Depression there is a regular change in the average values of the developed complex criterion $P_{comp.}$ Down the section, the P_{comp} values starting from OGC P_1 to OGC D_3f_2–C_1t are naturally increasing reaching maximum values for OGC D_3f_2–C_1t, then for OGC D_1-D_3f_1 the P_{comp} values decrease. These regularities are observed both for the areas with oil and gas content and without it. It should be noted that P_{comp} values for the areas with oil and gas content for OGC C_1v_2–C_2b, C_1v and D_3f_2–C_1t are higher than for the areas without oil and gas content. For OGC C_1v and D_3f_2–C_1t the average P_{comp} values for wells in the oil and gas bearing limits are more than 0.5, for wells outside the limits are less than 0.5. For OGC P_1, C_2vr, C_3-C_2ks, D_1–D_3f1, the average P_{comp} values for wells in the limits and beyond them are less than 0.5 and differ insignificantly. The graph based on the huge statistical data shows that the maximum difference is obtained for OGC D_3f_2–C_1t deposits. It probably indicates that the maximum differentiation of DOM into epigenetic and syngenetic occurred in the sediments of this complex.

The sediments located at depths from 1450 to 2700 m were in the main oil formation phase (MOP). It allows us to consider that the maximum "contribution" to the total oil and gas content formation of the Solikamsk Depression section was made by the DOM sediments of OGC D_3f_2–C_1t and to a lesser extent by C_1v.

The differentiation in the distribution of P_{com} values depending on the wells location relative to the oil and gas bearing areas allows to state that this phenomenon can act as estimation of the emergent nature of this system with respect to the zonal oil and gas content of the Solikamsk Depression [42].

Multidimensional models were constructed using stepwise regression analysis (RA) to account the diverse, multidirectional effects of the studied geochemical parameters on P_{com} for several variants. The calculation of regression coefficients in the constructed model was performed with the least squares method [13]. P_{com} serves as the dependent variable, and Kk, IR, C_{org}, OM, B_{CL}/B_{AB}, B_{PE}, B_{CL}, B_{AB}, HumA, and β values serve as independent factors. Initially, a multidimensional model was constructed on all data, regardless of the studied OGCs, then for all OGCs separately.

The analysis of multidimensional models constructed differentially on OGC, despite the fact that P_{com} values were calculated for all data, allowed us to establish, firstly, that in all cases the model formation began with the β parameter, and secondly, starting from the second step of regression equations construction, their formation occurred according to different scenario.

Analysis of the constructed multidimensional regression equations and comparison with the data obtained from P_{com} shows that more reliable models of the relationship between DOM characteristics and the total oil and gas content of the section can be achieved if the models are developed differentially for oil and gas bearing complexes of the SolD. The model formation from the second step of its construction is characterised by different sequences. It shows that the total oil and gas content of the Solikamsk Depression section was formed differentially due to different "contribution" of DOM characteristics.

For better understanding of the processes of the total oil and gas content formation in the Solikamsk Depression, the effect of Verkhnekamsk potassium-magnesium salts (VKMKS) section on the oil and gas

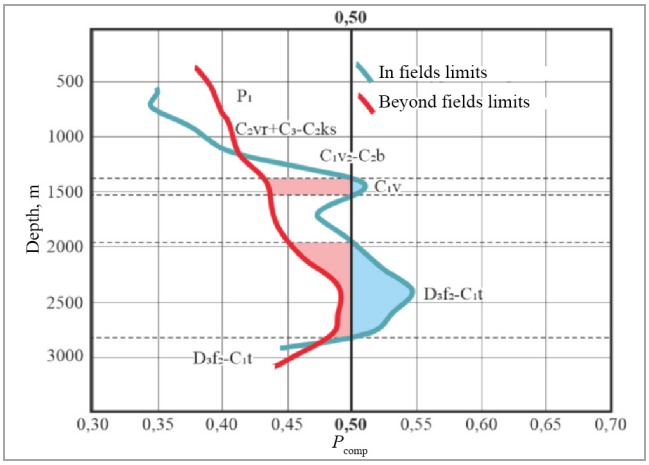

Fig. 2. Graphs of P_{comp} values changes by depth, NGC

content was estimated. For this purpose the average P_{com} values on several variants were compared.

It follows from the analysis that the average P_{com} values in oil fields limits and beyond them become statistically different, comparing these values in relation to the VKMKS location. There is no statistically significant difference between the average P_{com} values for the VKMKS area and those beyond its limits.

In contrast to the data obtained considering the VKMKS presence and beyond it, the average P_{com} values within and outside the field limits are statistically different when comparison is made between values obtained within the palaeoplateau area, beyond the palaeoplateau area and within the northwest edge of the KKTS. For variants, when the average P_{com} values in oil and gas content limits of the studied areas are compared, there are also statistical differences, but of much less statistical power. The data are similar for the areas without oil and gas content. It indicates that the P_{com} values formation due to geochemical parameters is to some extent controlled by the geological and tectonic conditions of well location.

Conclusion

Probabilistic-statistical estimation of the section geochemical characteristics shows that the total oil and gas content of the Solikamsk Depression section is largely controlled by the DOM characteristics. Statistical characteristics of geochemical parameters reveal significant differences in average values of the object classes in the studied OGCs.

The obtained individual linear models reflect the probability of oil-bearing for each parameter with different informativeness.

For complex account and determination of the optimal combination of geochemical parameters that effect the distribution of oil and gas content, a complex probabilistic P_{com} criterion for each OGC was developed. The obtained multidimensional regression equations in each complex have a different combination of parameters and direction of relationships, but all of them are reliable and statistically significant.

The statistical analysis confirmed that the sediments of the Upper Devonian-Tournaisian complex in the most part of the Solikamsk Depression were in the MON, where the maximum formation of mobile bitumoids took place, including hydrocarbons, effecting the formation of the total oil and gas content of the Solikamsk Depression section.

Fundamentally different changes in the values of the developed complex geochemical P_{com} criterion was established on depth for wells located in the oil and gas content limits and beyond them.

The most informative criterion, that most accurately indicates the relationship of DOM with the total oil and gas content of the section, is the bitumoid coefficient β.

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