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Development of a Zonal Model for Forecasting the Oil and Gas Potential of the YUS1 Formation by Geochemical Parameters

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Разработка зональной модели прогноза нефтегазоносности пласта ЮС1 по геохимическим параметрам

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The distribution of geochemical properties of rocks of the Bazhenov Formation (BF) by area and section has been refined, regularities have been searched, and conclusions have been obtained that have predictive power. Due to the high cost of continuous core sampling and pyrolysis of samples from BF intervals, the fragmentation and heterogeneity of the accumulated information, as well as the high value of knowledge about the oil-generating properties of BF rocks and their changes over the area, there is a need to increase the information content of the database of geochemical core studies and adapt its application in conditions of limited data.

To solve this problem, a database of results of geochemical studies was collected and analyzed, consisting of 5272 samples from 123 wells of 32 fields. As a result of the analysis, conclusions were obtained about the oil-generating properties of BF within the study area and the degree of maturity of the organic matter of the rock.

Two regression models were developed to predict the geochemical parameters of free hydrocarbon content, residual generation potential and total organic carbon from well logging data. An algorithm was implemented in the Python programming language to automate the calculation process. Using this algorithm and the resulting regression equation, the calculation of geochemical parameters was carried out in 390 wells in the study area that were not presented by core data, which significantly increased the detail and information content of predictive maps of the distribution of parameters over the area.

Using the data obtained, a geological and mathematical model was developed for predicting oil content by geochemical parameters. The developed model reflects the probability of oil content depending on the oil source properties of the rocks of the Bazhenov formation in the study area. The developed forecast model included the parameters of the organic carbon content in the rock, the current reservoir temperature and the thickness of the rocks of the Bazhenov formation.

Ключевые слова:
геохимические параметры, баженовская свита, база данных, геохимические исследования, регрессионные модели, прогноз нефтеносности, коэффициент корреляции, коэффициент детерминации, Сургутский свод.

Осуществлено уточнение распределения геохимических свойств пород баженовской свиты по площади и разрезу, проведен поиск закономерностей и получены выводы, имеющие прогнозную силу. В связи с высокой стоимостью сплошного отбора керна и пиролиза образцов из интервалов баженовской свиты, разрозненностью и неоднородностью накопленной информации, а также высокой ценностью знаний о нефтегенерационных свойствах пород Баженовской свиты и изменениях их по площади существует необходимость повышения информативности базы данных геохимических исследований керна и адаптации ее применения в условиях ограниченного количества данных.

Для решения данной проблемы была собрана и проанализирована база результатов геохимических исследований, состоящая из 5272 образцов 123 скважин 32 месторождений. В результате проведенного анализа были получены выводы о нефтегенерационных свойствах баженовской свиты в пределах территории исследования и степени зрелости органического вещества породы.

Для прогнозирования геохимических параметров содержания свободных углеводородов, остаточного генерационного потенциала и общего органического углерода по данным ГИС были разработаны две регрессионные модели. На языке программирования Python был реализован алгоритм, позволяющий автоматизировать процесс расчета. Используя данный алгоритм и полученное уравнение регрессии, был проведен расчет геохимических параметров в 390 скважинах на территории исследования, не освещенных керновыми данными, что существенно увеличило детальность и информативность прогнозных карт распределения параметров по площади.

Используя полученные данные, была разработана геолого-математическая модель прогноза нефтеносности по геохимическим параметрам. Разработанная модель отражает вероятность нефтеносности в зависимости от нефтематеринских свойств пород баженовской свиты на площади исследования. В разработанную модель прогноза вошли параметры содержания органического углерода в породе, современная температура пласта и мощность пород баженовской свиты.

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Introduction

The work was carried out as part of a complex study to identify regularities and forecast the oil-bearing capacity of Jurassic sediments in the northern part of the Surgut arch [1–4]. The study is aimed at searching for oil-bearing prospects in order to replenish the resource potential and identify priority targets for prospecting, appraisal and exploratory drilling.

The purpose of developing a geochemical forecast model is to establish a quantitative relationship between the oil-maternal properties of the Bazhenov Formation rocks and the oil bearing capacity of the Upper Jurassic sediments.

The oil-bearing capacity of the Jurassic sediments of the study area, like other petroleum systems, is a subject to the laws and influence of various factors, as: hydrocarbon presence in the system, vertical and lateral migration of hydrocarbons, the presence of a reservoir in the formation and traps for hydrocarbon accumulation [5–8]. In this work, the main attention is paid to the study of the oil source rock properties and its influence on the oil bearing capacity of the YUS1 reservoir.

The object of the study is the oil-bearing formation YUS1 of the Vasyugan Formation in the northern part of the Surgut arch within the boundaries of Territorial and Production Enterprise "Kogalymneftegaz". Lithologically, it is represented by interbedded sandstones and siltstones underlain by deep-water sediments of the transgressive series in the lower part of the Vasyugan Formation. The YUS1 formation is one of the main production targets in the study area and has a high oil-bearing potential [2].

The generation properties of source rocks are one of the key factors determining the prospects of oil-bearing sediments. Previously, a number of researches aimed at studying the properties of the main oil-generating formation of the West Siberian basin – the Bazhenov Formation – were carried out in the study area and adjacent territories, the main results of which are presented in the works [9–15].

Geochemical Database Analysis

The database of pyrolytic studies performed by Rock-Eval method on core samples from the Kogalym and Langepas-Pokachev regions was used to analyse and study the regularities of source rock properties. Pyrolysis of core samples using the Rock-Eval method is based on thermal decomposition of organic compounds contained in rocks and measurement of gas quantity and quality emitted during the decomposition process.

The results of the study provide information on such parameters as free hydrocarbon content (S_1), residual generation potential (S_2), amount of pyrolysed CO_2 (S_3), total organic carbon (TOC) and temperature of maximum hydrocarbon yield during cracking ($T_{\max}$).

The generalised database of the studied samples conducted by different organisations in the study area consisted of 5.272 core samples from 123 wells within "Langepasneftegaz", "Pokachevneftegaz", "Povkhneftegaz" and "Kogalymneftegaz". The samples cover a wide stratigraphic range from pre-Jurassic to Cretaceous sediments, with the largest number of samples studied belonging to the Bazhenov Formation – 1.739 samples from 84 wells and Cretaceous sediments – 1.627 samples from 59 wells.

The general sample selection of a wide stratigraphic range is characterised by a large scale of all parameters values; therefore, statistical analysis was carried out separately for Cretaceous, Middle and Lower Jurassic sediments, as well as for the Bazhenov and Vasyugan formations. Statistical characteristics of pyrolytic parameters of the Bazhenov Formation samples are given in Table 1.

According to the classification of oil and gas source rocks [16], the Bazhenov Formation of the study area in terms of organic carbon content belongs to the class of very rich, the average value of TOC is 8.8 %, and the total content of allochthonous and autochthonous bitumoids on average varies around 50 mg/g of rock. According to the classification of organic matter maturity, the rocks of the Bazhenov Formation belong to the category of early maturity rocks, most of the samples are characterised by hydrocarbon yield temperatures in the range from 435 to 445° C, only 2 % of the studied samples characterise the intervals of rocks at the generation peak. According to the Van Krevelen diagram, the predominant type of kerogen is oil-producing kerogen II.

Development of Models for Geochemical Parameters Estimation on Well-Logging Data

The primary analysis of the database structure showed that, despite the large number of studied samples, the study of individual sediments and formations is not systematic, as evidenced by the distribution graph of the studied samples number from the Bazhenov Formation (BF) sediment interval (Fig. 1).

Due to the circumstances, continuous core sampling from the entire BF bedding interval is performed in single wells, which are usually located at a large distance from each other. It limits the possibility of model construction of parameter distribution over the area and reduces the informativeness of such models. Most of the studied samples represent a partial section of the BF, either roof or bottom. However, to use the results in model construction is not always fair, due to vertical heterogeneity of the BF rock properties.

Table 1

Statistical characteristics of geochemical parameters

Parameter	Arithmetic mean	Minimum	Maximum	Standard deviation	Distribution
S_1, mg HC/g sam	4.70	0	20.85	2.92	Log-normal
S_2, mg HC/g sam	45.15	0.0700	210.93	32.42	Log-normal
$T_{\max}$, °C	437.76	409	451	5.21	Normal
TOC, %	8.78	0.10	28.9	5.34	Log-normal

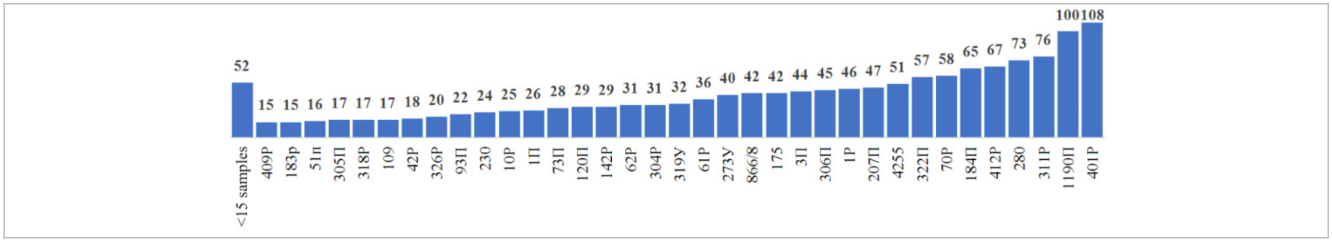


Fig. 1. Distribution graph of studied samples number of the Bazhenov Formation by wells

Table 2

Correlation matrix of geochemical and geophysical parameters

Parameter	BK	IK	GK	NKT	lnBK	lnIK	GK/NKT	lnGK/NKT
$S_1 + S_2$	0.119	-0.093	0.630	-0.370	0.221	-0.089	0.656	0.598
TOC	0.117	-0.091	0.613	-0.358	0.206	-0.083	0.635	0.566

Note: *red colour indicates correlation values with statistical significance.

Given the limited data on Bazhenov Formation rocks obtained from pyrolytic studies, correlation and regression analyses were performed to determine relationships between core and logging. It helped to calculate geochemical parameters in wells that were not analyzed with the Rock-Eval method.

The tasks of logging data interpretation in unconventional, kerogen-bearing reservoirs are studied by many authors and research groups [17–28]. One of the most frequently cited works in the field of geochemical parameter estimation from logging data is the study of J. Schmoker [29], who considers the method of organic carbon content calculation based on gamma- and gamma-gamma density logs, and uses equation (1) to describe the dependency.

$$V_{\text{ов}} = (\gamma_{\text{в}} - \gamma) / (1.378 \cdot A), \qquad (1)$$

where $\gamma_{\text{в}}$ – gamma log readings in the rock unsaturated with hydrocarbons; γ – gamma log readings of the studied formation, A – inclination angle of the intersection points on the graph of radioactivity and density dependency.

Many researchers estimated the organic matter content in rocks. For example, Soviet scientists [30] found a relationship between the organic carbon content and gamma activity of samples, and American researchers B.L. Meyer and M.H. Nederlof [31] established a dependency on the rock density. In June 2017, Schlumberger published a patent [32], which described an algorithm for estimating the maturity and geochemical parameters of source rocks based on log data. Many methodologies confirm that the geochemical parameter estimation is applicable only for certain areas and is a subject to adjustments for new areas based on actual data.

In a number of works, the correlation between carbon content and geophysical parameters was established, and in aggregate with the available observation database, the focus was on the parameters $S_1 + S_2$ and TOC due to their high significance in determining the generation properties of source sediments.

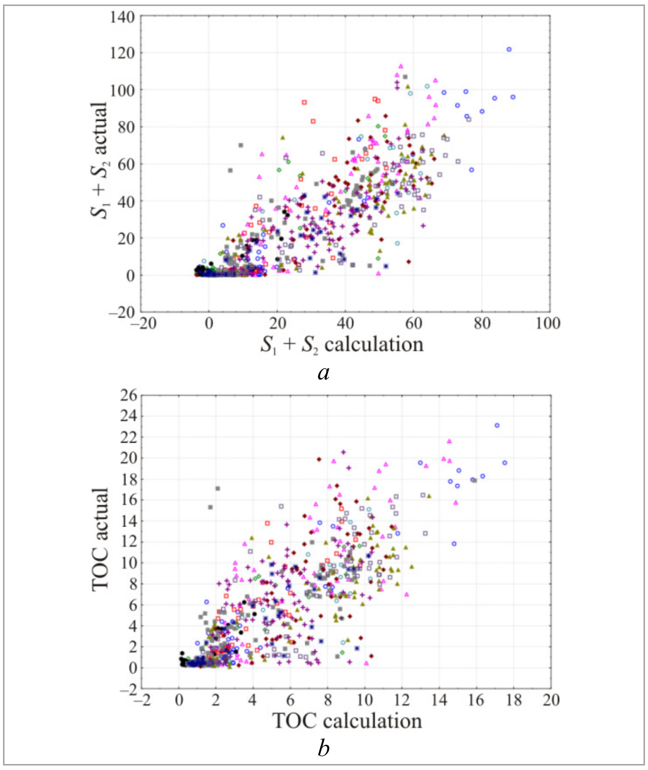
Based on available constraints, the selection for regression analysis was reduced to 580 samples in 12 wells most systematically covered by the studied samples, in which the binding of samples to depth intervals is unquestionable.

The next stage was to search for "core – logging" dependencies. For this purpose the results of core examination were compared with geophysical parameters of the main logging complex (BK – resistivity logging (Ohm·m), IK – induction logging (mSm), GK – gamma logging (mRg/h), NKT – thermal neutron logging (imp/min)), as well as their derivatives (lnBK, lnIK, GK/NKT, ln[GK/NKT]), the results of correlation analysis are given in Table 2.

Analysis of the correlation matrix showed high correlation of geochemical parameters $S_1 + S_2$ and TOC with gamma logging (0.63 and 0.613 respectively) and statistically significant correlation with other geophysical parameters. By the method of multiple regression analysis the models with correlation coefficients from 0.7 to 0.77 were obtained, but due to a large number of variables and problems with model performance outside the BF intervals, their applicability was questionable.

The models were improved by adding samples from the Achimov Formation, the Georgievskaya Formation, and the Yu1 Formation with expanding to 759 samples, where 580 samples belonged to the BF interval and and 179 samples – to the intervals of the Achimov, Georgievskaya and Vasyuganskaya formations. Analysis of intermediate results showed that increasing the number of variables in the model does not have a linear relationship with the value of the achieved correlation coefficient, so the method of multiple regression analysis was changed to Backward stepwise.

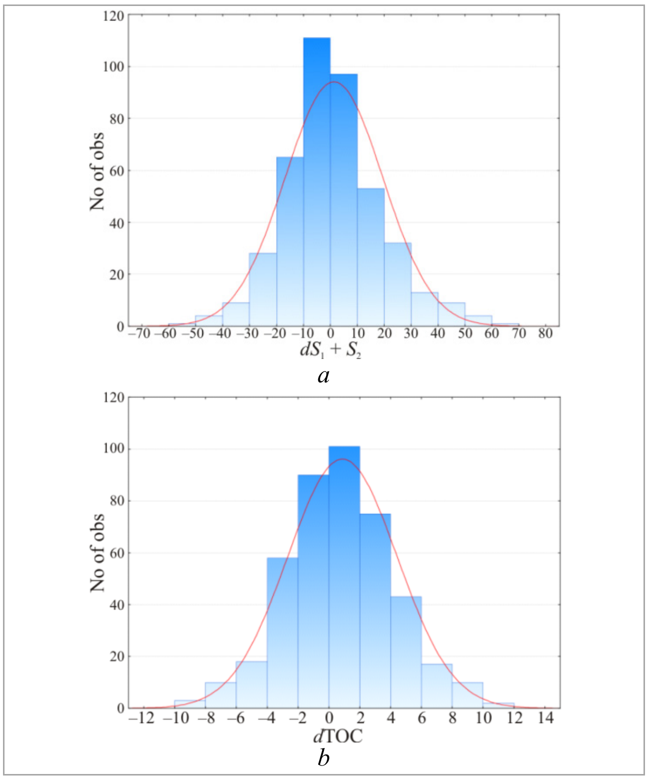
The final iterations allowed to develop a regression model with high correlation and determination coefficients, the dependence formulas are presented in equations (2) and (3), and the graphs of parameter dependencies are shown in Fig. 2 (*a, b*) (the points ranking corresponds to different wells). The mean values of the difference between the determined and actual values for the parameters $S_1 + S_2$ and TOC are 0.78 and 0.65, respectively, and the standard deviation is 16.2 and 3.2. The estimation errors have a normal distribution, the histograms of the distribution density are shown in Fig. 3.



a

b

Fig. 2. Comparison of actual and calculated parameter values: *a* – $S_1 + S_2$; *b* – TOC



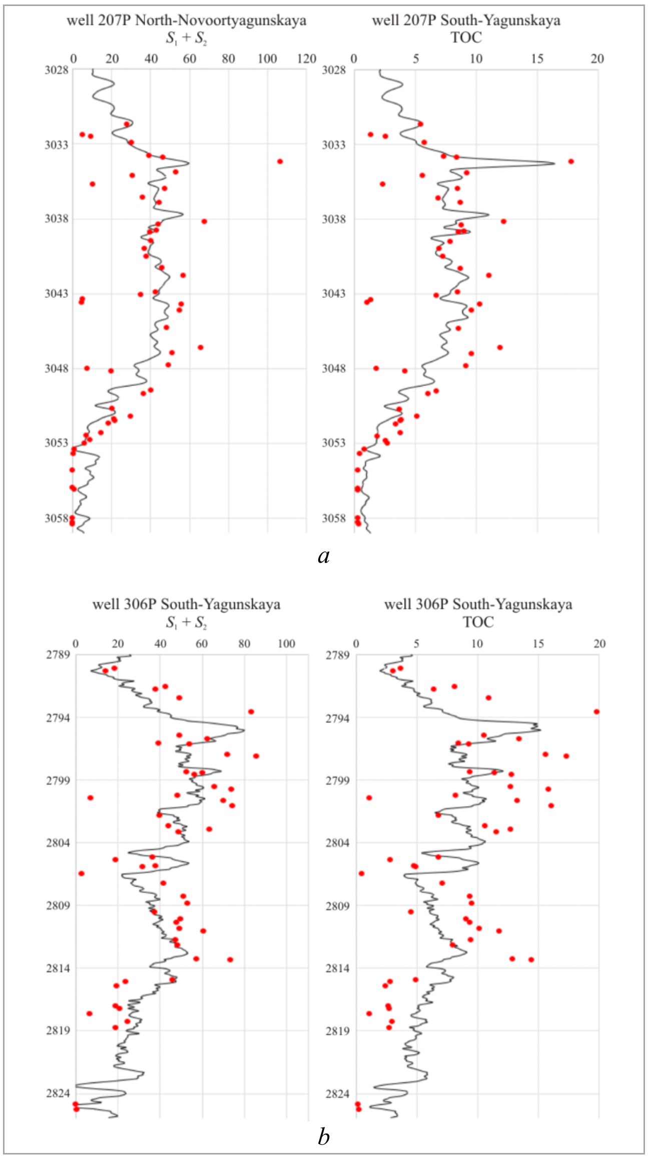
a

b

Fig. 3. Histograms of the estimation errors distribution: *a* – $S_1 + S_2$; *b* – TOC

$$S_1 + S_2 = -21.63 + 2.74 \cdot \text{NKT} + $$
$$+ 4.63 \cdot \ln\text{BK} - 1.68 \cdot \ln\text{IK} + 18.26 \cdot \ln(\text{GK/NKT});$$
$$r = 0.84,\ R^2 = 0{,}706 \qquad (2)$$

$$\text{TOC} = -1.84 + 0.103 \cdot \text{GK} + $$
$$0.85 \cdot \ln\text{BK} + 1.07 \cdot \ln(\text{GK/NKT});$$
$$r = 0.816,\ R^2 = 0.67 \qquad (3)$$



a

b

Fig. 4. Schemes of calculated and actual parameters comparison $S_1 + S_2$ (left) and TOC (right) for wells: *a* – 207P of the North-Novoortyagunskaya area; *b* – 306P South-Yagunskaya area

The obtained dependence equations made it possible to calculate the distribution of parameters $S_1 + S_2$ and TOC of the continuous curve in the whole Bazhenov Formation interval and to compare them with the actual results determined from the core study; fragments of the comparison schemes are shown in Fig. 4.

Despite the relatively large scatter of individual results values of core parameters from the calculated curve, the obtained regression model allows to approximate these parameters with sufficient accuracy for the whole BF profile. To assess the reliability and applicability of the regression models, Pearson's chi-squared test χ^2 was applied for a number of wells. The results showed that the value of χ^2 statistics when comparing samples of actual and calculated values in wells allows us to accept the null hypothesis, i.e. the distributions of the expected and observed variable (actual and calculated values) can be considered the same for the aggregate parameter sampling $S_1 + S_2$ $\chi^2 = 0.41$ at $p < 10^{-20}$, for TOC $\chi^2 = 3.04$ at $p < 10^{-25}$.

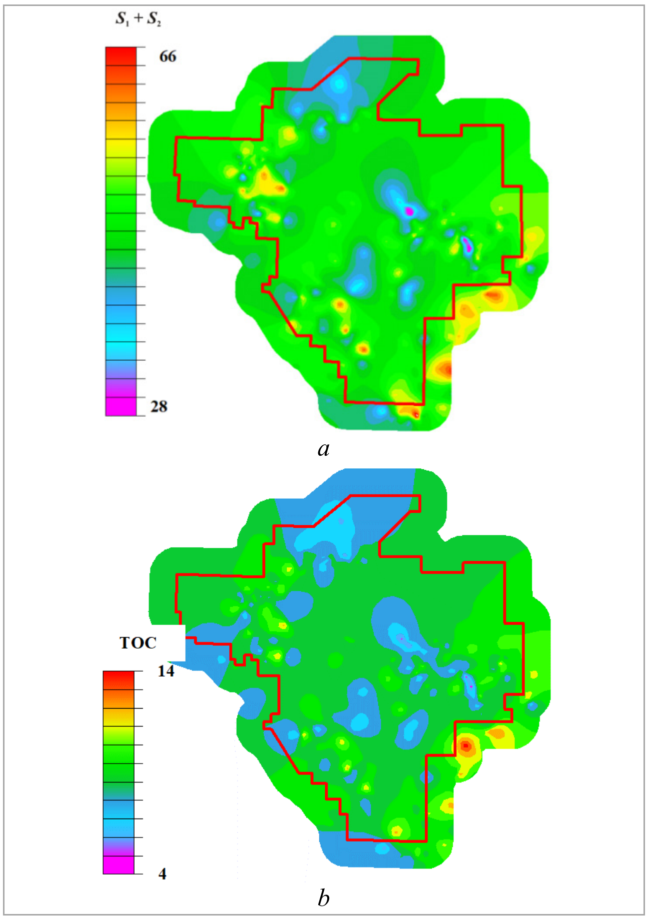


Figure 5. Area schemes of parameters distribution: *a* – S_1+S_2; *b* – TOC

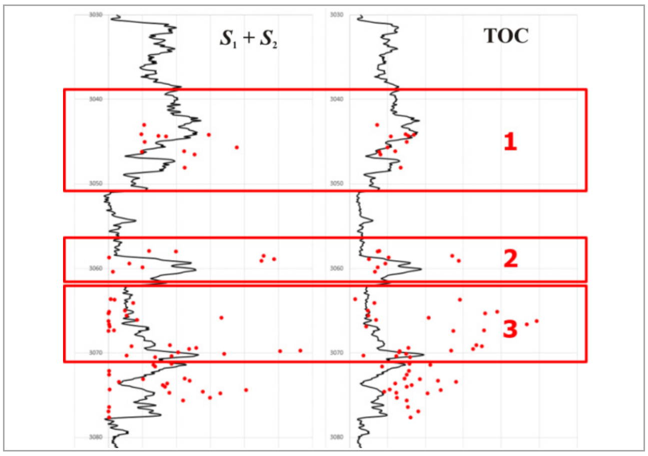


Fig. 6. Comparison scheme of calculated and actual parameters: S_1+S_2 (left) and TOC (right) at well 280 of Imilorskaya area

To calculate S_1+S_2 and TOC parameters for the entire study area, a database of las-files was assembled and the BF profile was correlated. The complexity of further calculations was in creating a database with samples of selected log curves, calculating the necessary derivatives from them and separating the BF interval from the entire well profile. In order to automate the process and reduce labour costs, an algorithm was implemented in the Python programming language. The result of the algorithm is a summary report in excel-file, in which averaging of the calculated data in the BF interval with reference of coordinates, well number and calculation intervals is carried out. Thus, to calculate geochemical parameters for an unlimited number of wells, it is necessary to prepare a las-file and preliminary correlate the sediments in the formation of which the calculation should be performed. The average time required to perform the calculation for 100 wells is about 40 seconds, which significantly reduced the time required to perform this operation.

The obtained regression models made it possible to calculate and obtain average values of geochemical parameters in wells not included to pyrolytic studies. The primary estimation of the obtained results was also carried out, and maps of S_1+S_2 and TOC parameters distribution over the area were constructed (Fig. 5).

According to the obtained schemes it is possible to distinguish zones with increased values of parameters, which are probably zones of oil generation in the north-west of the territory, as well as a stable trend for the parameters increase in the east of the territory.

The obtained results open up opportunities for more detailed forecasting of oil-source BF rock properties in the study area with some additional parameters used, such as the degree of organic matter maturity and thickness of oil-source rock deposits.

The developed model has limitations and its own zone of uncertainty due to the anomalous section of the Bazhenov Formation. The main difficulty is interbedding of terrigenous rocks and thin layers of Bazhenov shales in an anomalous section which is clearly demonstrated by the example of well 280 in the Imilorskaya area (Fig. 6).

Three areas can be distinguished in the Bazhenov Formation section of well 280: 1) an area of undisturbed or slightly transformed Bazhenov shale; 2) an area of Bazhenov shales development with interlayers of terrigenous rocks; 3) an area of terrigenous rock development with thin interlayers of Bazhenov shale. For site 1, the convergence of calculated and actual parameter values is relatively high, typical for wells located in the zones of normal BF section. Site 2 is characterised by a large scatter of parameters determined from the core sample, with high variability of properties in a narrow depth interval. The higher values of the calculated curves here indicate the advantage of Bazhenov shales over terrigenous interlayers in the analyzed interval. Site 3 is likely more represented by terrigenous rocks with thin interlayers of Bazhenov shales, as confirmed by the research results. This interval is also characterised by an anomalously weak correlation between calculated and actual geochemical parameters.

Development of a Probabilistic-Statistical Forecast Model

A number of area distribution models were developed to study and establish a quantitative correlation between geochemical parameters. In developing the forecast model, such parameters as the temperature of the YUS1 reservoir (T), TOC, S_1+S_2 and the thickness of Bazhenov Formation rocks (hBag) were analysed.

In the study area, the Bazhenov Formation sediments are complicated by zones of anomalous section development (ASBF), where sandy bodies are embedded in bituminous argillite. There are several hypotheses about their formation [33-45], but this study was carried out within the paradigm developed by V.F. Grishkevich connecting the mechanism of ASBF formation with landslide processes and the intrusion of Achimov formations.

The Bazhenov Formation rock thickness distribution model was developed to estimate the thickness of the original accumulated bituminous argillite deposits. The roof of the Bazhenov Formation was constructed by generalising the structural maps from seismic operation data and, in the ASBF development zones, by the method of convergence from the roof of the YUS1 formation. The geochemical parameter distribution in the ASBF zones was calibrated to actual pyrolysis results in wells with anomalous section that penetrated a sufficiently thick series of undisturbed Bazhenov shales, and also calculated by interpolation.

While developing the forecast model, data of current reservoir temperatures were also used as an indirect parameter characterising heat flow, a factor influencing the processes of oil generation and migration from source rocks. The temperature distribution model for the area was developed on the basis of actual thermometry data obtained during downhole logging; the record that corresponds to the thermometry before the first compression cycle was used as the required curve. The temperature distribution model was developed taking into account the depth trend of the YUS1 reservoir, and a graph of temperature dependency on depth is shown in Fig. 7.

According to the principles of "autofluid fracturing" and downward migration of protopetroleum from Bazhenov Formation rocks to the underlying reservoir proposed by I.I. Nesterov [46], models of geochemical parameter distribution for different thickness intervals from the series base of the Bazhenov Formation were developed to estimate source rock properties. Using these parameters is likely to help to estimate in details the properties of rocks exactly of the part that generated HC oil deposits of the YUS1 formation.

The results of Student's *t*-criterion parameter analysis used in the development of the oil-bearing capacity forecast model are shown in Table 3.

Among the geochemical parameters characterising the content of bitumoids and organic carbon in the rock, the most informative are those for the lower 20-30 % of the Bazhenov Formation thickness. The parameters for the lower quarter (25 %) of the petroleogenetic formation thickness were used in developing the forecast model.

Then, a model for the oil-bearing capacity forecast of the Yu1 reservoir based on geochemical parameters was developed using a stepwise linear discriminant analysis method. The model included three variables: thickness of the Bazhenov Formation (hBag), current reservoir temperature (T) and organic carbon content in the lower 25 % of the Bazhenov Formation thickness (*h* TOC_25 %).

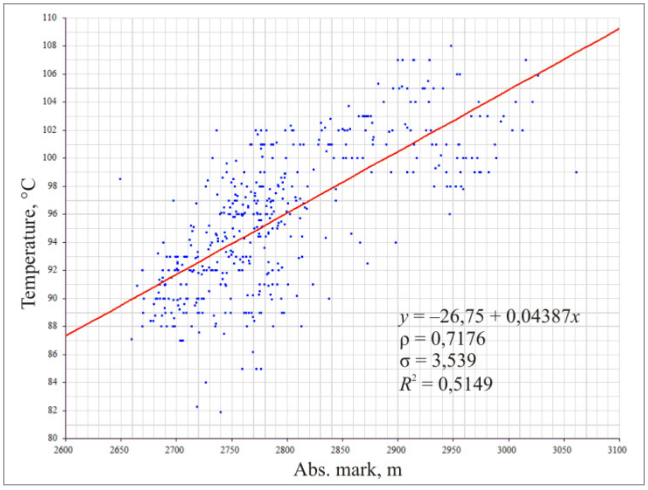


Fig. 7. The graph of temperature dependency on depth for the YUS1 reservoir

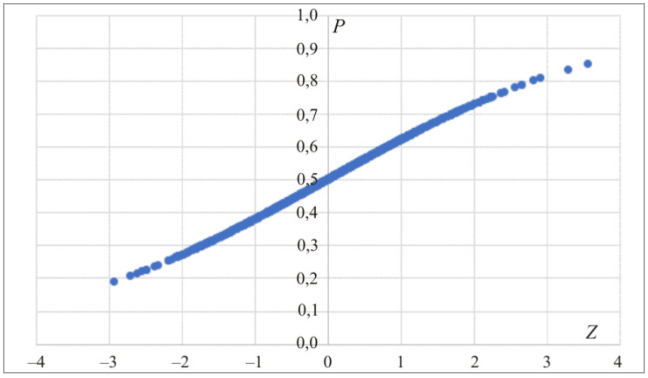


Fig. 8. Graph of oil-bearing probability dependency on the value of discriminant function

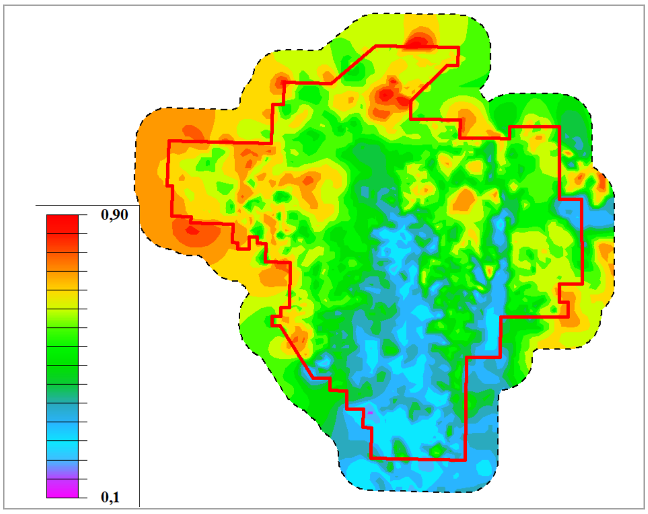


Fig. 9. Scheme of oil bearing capacity probability of Yu1 formation by geochemical parameters

The canonical equation of the forecast model is shown in the equation (4), the graph of probability dependence on the discriminant function value is shown in Fig. 8, and the scheme of oil-bearing capacity probability of the Yu1 formation based on geochemical parameters is shown in Fig. 9.

$$Z = -0.1016 \cdot \text{hBag} + 0.168 \cdot T - 0.046 \cdot [h\text{TOC\_25 \%}] - 11.99 \qquad (4)$$

Table 3

Statistical characteristics of geochemical parameters

Variable	Oil	Water	*t*-criterion
	(mean value)		
	Standard deviation		*p*-value
hBag	26.079	27.303	-4.410
	3.976	4.174	0.000
$S_1 + S_2$	45.028	44.287	2.211
	4.791	5.057	0.027
TOC	7.434	7.340	1.345
	1.039	1.017	0.179
TOC·Bag	193.069	200.556	-2.852
	35.903	41.440	0.004
$S_1 + S_2$·Bag	1171.779	1209.839	-2.574
	204.399	230.946	0.010
T	95.467	93.798	5.704
	4.737	3.646	0.000
$h{\cdot}S_1 + S_2$_5 %	31.452	33.402	-3.368
	8.302	8.707	0.001
h·TOC_5 %	4.962	5.313	-3.914
	1.274	1.355	0.000
$h{\cdot}S_1 + S_2$_10 %	68.570	73.357	-4.060
	16.752	17.913	0.000
h·TOC_10 %	10.750	11.565	-4.392
	2.641	2.812	0.000
$h{\cdot}S_1 + S_2$_20 %	163.614	175.204	-4.541
	36.606	38.351	0.000
h·TOC_20 %	25.477	27.436	-4.644
	6.012	6.379	0.000
$h{\cdot}S_1 + S_2$_30 %	273.749	291.461	-4.593
	54.848	58.508	0.000
h·TOC_30 %	42.928	45.936	-4.550
	9.379	10.056	0.000

Note: hBag – thickness of Bazhenov Formation sediments; TOC·Bag – product of C_{org} content in the rock and Bazhenov Formation thickness; $S1 + S2$·Bag – product of bitumoid content in the rock and Bazhenov Formation thickness; T – current reservoir temperature; $h{\cdot}S1 + S2$_N % – product of bitumoid content in N % of the Bazhenov Formation thickness (from the bottom) and the corresponding thickness of bituminous sediments; h·TOS_N % – product of C_{opr} content in N % of the Bazhenov Formation thickness (from the bottom) by the corresponding thickness of bituminous sediments.

Conclusion

As a result of the research, a database of geochemical results consisting of 5,272 samples from 123 wells of 32 fields was collected and analysed. The results of the analysis are considered as conclusions of the oil-generation properties of the Bazhenov Formation within the study area and the maturity of the rock organic matter.

Two regression forecast models of $S_1 + S_2$ and TOC geochemical parameters from logging data were developed. The forecast model of $S_1 + S_2$ parameter consists of four variables, the correlation coefficient of the model with actual data is 0.84, the coefficient of determination $R^2 = 0.706$. The forecast model of TOC parameter consists of three variables, the correlation coefficient of the model with actual data is 0.816, the coefficient of determination $R^2 = 0.67$.

An algorithm was developed in the Python programming language to automate the calculation process. The developed algorithm applies the regression equation to the specified geophysical parameters using a pre-prepared list of las-files and makes a report with averaged values of parameters within the specified interval with reference to coordinates and well data.

Using the algorithm and the obtained regression equation, geochemical parameters were calculated for 390 wells in the study area not covered by core data, which significantly increased the detail and informativeness of the forecast maps of parameter distribution over the area.

The developed forecast model has relatively low recognisability – 60 % of the sample, 62 % for oil-bearing wells and 58 % for wells with no oil-bearing capacity. However, considering the fundamental contribution of the geochemical factor to oil-bearing capacity and the complexity of hydrocarbon deposits formation, the obtained result will be taken into account in the process of studying the patterns and forecasting of oil-bearing capacity.

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