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Application of multilevel probabilistic-statistical modeling in forecasting the oil and gas potential of structures on the example of the south of the Perm Krai

Aleksey L. Yuzhakov

PermNIPIneft branch of LUKOIL-Engineering LLC in Perm (3a Permskaya st., Perm, 614015, Russian Federation)

Применение многоуровневого вероятностно-статистического моделирования при прогнозе нефтегазоносности структур на примере юга Пермского края

А.Л. Южаков

Филиал ООО «ЛУКОЙЛ-Инжиниринг» «ПермНИПИнефть» в г. Перми (Россия, 614015, г. Пермь, ул. Пермская, 3а)

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structure, oil and gas potential, hydrocarbons, regression analysis, reflecting horizon, organic matter, geochemistry, hydrogeology, forecasting, probabilistic-statistical model, tectonic element, generation, accumulation, reservoir safety, hydrogeology.

The high geological knowledge of the south of the Perm Krai makes it possible to collect a large amount of data to determine the oil and gas potential of the structures. The main criteria in the distribution of oil and gas content are the processes of hydrocarbon generation, accumulation, as well as the safety of hydrocarbon deposits from physical and chemical destruction. Data on geochemical studies of the oil and gas source suite (Upper Devonian Semiluk deposits) were used as criteria for the generation of hydrocarbons to assess the generation potential of the deposits. Based on the conducted seismic surveys, local structures were identified in the Visean complex of deposits. The surfaces of the regional, zonal and local components were calculated, the average values of the structural parameters were obtained to assess the influence of the accumulation criteria. Hydrogeological parameters were used as criteria for the safety of hydrocarbon deposits.

To predict the oil and gas potential of the structures, multilevel probabilistic models were used. At the first level, individual statistical models were calculated for each of the parameters used, as well as complex probabilistic parameters separately for each group of criteria. At the second level, complex models were calculated taking into account all available information on the generation, accumulation and preservation of hydrocarbon deposits for the entire study area. A regression analysis was carried out with a stepwise increase in the sample of initial data. This analysis made it possible to evaluate the influence of each individual group of criteria on the saturation of hydrocarbon structures. At the third level, the calculated models were differentiated by individual large tectonic elements that are part of the study area. The constructed models of the 3rd level proved that in the territory of the south of the Perm Krai, the forecast of the oil and gas potential of local structures should be carried out separately for tectonic elements. Based on the results of the oil and gas potential forecast, 15 structures potentially saturated with hydrocarbons and 80 potentially empty structures were identified.

Ключевые слова:
структура, нефтегазоносность, углеводороды, регрессионный анализ, отражающий горизонт, органическое вещество, геохимия, гидрогеология, прогнозирование, вероятностно-статистическая модель, тектонический элемент, генерация, аккумуляция, сохранность залежей, гидрогеология.

Высокая геологическая изученность территории юга Пермского края позволяет собрать большой массив данных для определения потенциала нефтегазоносности структур. Основными критериями в распределении нефтегазоносности структур являются процессы генерации углеводородов, аккумуляции, а также сохранности залежей углеводородов от физико-химического разрушения. В качестве критериев генерации углеводородов для оценки генерационного потенциала отложений использованы сведения о геохимических исследованиях нефтегазоматеринской свиты (семилукские отложения верхнего девона). На основании проведенных сейсморазведочных работ, в визейском комплексе отложений были выделены локальные структуры. Рассчитаны поверхности региональной, зональной и локальной составляющих, получены средние значения структурных параметров для оценки влияния критериев аккумуляции. В качестве критериев сохранности залежей углеводородов использованы гидрогеологические параметры.

Для прогноза нефтегазоносности структур использованы многоуровневые вероятностные модели. На первом уровне рассчитаны индивидуальные статистические модели по каждому из используемых параметров, а также комплексные вероятностные параметры отдельно по каждой группе критериев. На втором уровне рассчитаны комплексные модели с учетом всей имеющейся информации о генерации, аккумуляции и сохранности залежей углеводородов для всей территории исследования. Проведен регрессионный анализ с пошаговым увеличением выборки исходных данных. Данный анализ позволил оценить влияние каждой отдельной группы критериев на насыщение структур углеводородов. На третьем уровне рассчитанные модели были дифференцированы по отдельным крупным тектоническим элементам, входящим в состав области исследования. Построенные модели третьего уровня доказали, что на территории юга Пермского края прогноз нефтегазоносности локальных структур следует проводить отдельно по тектоническим элементам. По итогам проведенного прогноза нефтегазоносности выявлено 15 потенциально насыщенных углеводородами структур и 80 потенциально пустых структур.

© **Aleksey L. Yuzhakov** – Researcher of the Petrophysical Modeling Department (tel.: +007 (342) 233 63 59, e-mail: Alexey.yuzhakov@pnn.lukoil.com).

© **Южаков Алексей Леонидович** – научный сотрудник отдела петрофизического моделирования (тел.: +007 (342) 233 63 59, e-mail: Alexey.yuzhakov@pnn.lukoil.com).

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Introduction

In the conditions of increasing complexity of oil and gas prospecting, it is necessary to carry out research to identify previously undrilled structures and forecast their oil and gas content. The territory of the southern part of Perm Krai is characterized by high exploration, which allows collecting a large amount of data to identify structures and determine their oil and gas bearing potential [1].

The main oil and gas bearing complex (OGC) of the Volga-Ural oil and gas province is the Lower-Middle Visean OGC, which is characterized by the largest amount of explored hydrocarbon reserves.

The purpose of this work is to identify and predict the oil and gas content of local structures of the Visean sedimentary complex in the southern part of Perm Krai by means of multilevel probabilistic modeling.

Identification of Local Structures

The Lower-Middle Visean OGC includes the reflecting horizon (RH) IIK, which is confined to the roof of the Tula terrigenous sediments [2, 3]. Data on all 2D and 3D seismic surveys conducted in the study area were collected for the RH IIK and a single surface was constructed. The surfaces of regional, zonal, and local components characterized by the presence of structures of the 1st, 2nd, and 3rd order, respectively, were calculated for this OG [2, 4–7]. The most interesting is the local component of RH IIK, on the surface of which the last closed isohypses of anticlinal structures of the 3rd order were identified. The individual obtained structures are divided into three classes: empty (proved absence of oil and gas content), saturated (commercial oil inflow was obtained) and predicted (not previously identified).

Criteria of Hydrocarbon Generation in Predicting the Oil and Gas Content of Structures

The main criteria for predicting the oil and gas content of structures are the processes of generation, accumulation, and preservation of hydrocarbon (HC) deposits [8–12]. First of all, the generation potential of the territory and its influence on the oil and gas content of local structures of Visean sediments were analyzed [13–17]. Geochemical parameters of the oil and gas mother formation (Semiluk deposits of the Upper Devonian) were used as generation criteria: organic carbon content (C_org); chloroform bitumoid content; reflectivity of vitrinite and thickness of Semiluk deposits of the Upper Devonian. Average values of geochemical parameters were collected for each selected structure.

Individual statistical models were constructed for all geochemical parameters, reflecting the influence of an individual parameter on the probability of the presence of a deposit [18-25]. Fig. 1 shows the individual statistical model on the example of parameter *C_org*: we can see how the probability of deposit presence *P*(*C_org*) changes depending on the value of parameter *C_org*. When *C_org* increases above 5 %, *P(C_org)* increases above 0.5 fractions of units. The values of *P(C_org)* range from 0.25 to 0.75 fractions of units.

Based on individual statistical models on generation criteria, the complex saturation probability of HC structures *(Pg)*, which is a level 1 model, is obtained. The formula for calculating *Pg* (1):

$$P_g = \frac{P_1 \cdot P_2 \cdot P_n}{P_1 \cdot P_2 \cdot P_n + (1-P_1)\cdot(1-P_2)\cdot(1-P_n)}, \quad (1)$$

$$clas = 60.5\ \%,$$

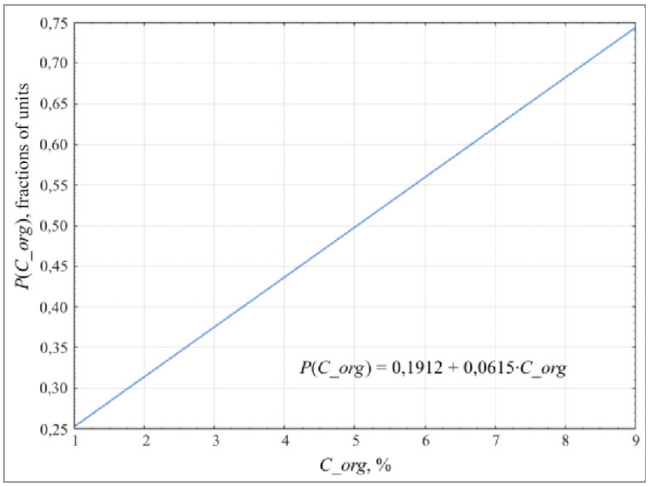

Fig. 1. Individual statistical model of the parameter *C_org*

where *clas* – correct classification rate, P_1, P_2, P_n – values of saturation probability by individual statistical models.

The correctness of determinations on the complex probability of saturation of hydrocarbon structures on the basis of generation criteria is 60.5 %. It was revealed that all used geochemical parameters significantly affect the saturation of local structures of Visean sediments. It is also noted that the generation criteria are not sufficient for the most reliable prediction of oil and gas content of structures.

Criteria of Hydrocarbon Accumulation in Predicting the Oil and Gas Content of Structures

In addition to generation criteria, accumulation criteria, reflecting the presence of a structural trap for HC accumulation, influence the saturation of structures with HC. Structural parameters were used as criteria of HC accumulation: area; amplitude (*Ampl*); distance to tectonic discontinuities; structure intensity and the highest absolute mark of the structure. The parameters of surface curvature and surface inclination azimuth were also calculated from the local component of the RH IIK [26, 27]. The calculated mean values of the parameters for each structure allowed the construction of individual statistical models. The analysis of the obtained models showed that the amplitude parameter has the greatest influence on the presence of HC deposits. The values of *P(Ampl)* vary from 0.21 to 0.96 fractions of units. The average value of *P(Ampl)* for empty structures is 0.39, and for saturated structures - 0.61 fractions of units.

The obtained individual statistical models for each parameter allowed us to construct a comprehensive level 1 model of the accumulation criteria (P_{am}). Formula for calculation P_{am} (2):

$$P_{am} = \frac{P_1 \cdot P_2 \cdot P_n}{P_1 \cdot P_2 \cdot P_n + (1-P_1)\cdot(1-P_2)\cdot(1-P_n)}. \quad (2)$$

$$clas = 72.5\ \%.$$

The share of correct classification according to the complex model is 72.5 %, which is higher than in calculating the model according to the generation criteria and indicates a greater contribution to the saturation of HC structures by the accumulation criteria.

Criteria of HC Deposit Preservation when Forecasting the Oil and Gas Content of Structures

In addition to the data on generation and accumulation, hydrogeological parameters determined in the study area

were used to show the preservation of HC deposits from chemical and physicochemical destruction: mineralization of waters of the terrigenous part of the Visei (*Min(Vt)*); mineralization of waters of the carbonate part of the Visei sediments; average chlor-bromine content in waters of the carbonate Visei; average sulfur content in waters of the carbonate Visei; average sodium-chlorine content in waters of the terrigenous and carbonate Visei [28].

Average values of hydrogeological parameters for each structure were calculated. The analysis of individual statistical models has shown that there is a relationship between the parameters and the presence of hydrocarbon deposits. Among the hydrogeological parameters, the dependence of the probability of saturation of structures on the water salinity of terrigenous sediments of Visei is inverse. Other dependences on hydrogeological parameters are linearly expressed and represent a direct relationship between the saturation probability and the parameter used.

On the basis of individual statistical models on accumulation criteria the complex probability of saturation of structures of HC (*Ps*), which is a model of the 1st level, is obtained. Formula for calculation P_s (3):

$$P_s = \frac{P_1 \cdot P_2 \cdot P_n}{P_1 \cdot P_2 \cdot P_n + (1-P_1)\cdot(1-P_2)\cdot(1-P_n)}, \quad (3)$$

$$clas = 59.6\ \%.$$

The percentage of correctness of the complex saturation probability determinations according to the conservation criteria was the lowest among the criteria used in the study, which indicates a smaller influence on the saturation of HC structures, in contrast to the generation and accumulation criteria.

Comprehensive Forecast of Oil and Gas Content of Visean Sediments in the Southern Part of Perm Krai

The construction of level 1 models makes it possible to qualitatively move to level 2 models, which include studies on the entire set of criteria for the total area of research. Level 2 models were built on the basis of a complex formula for calculating the probability of saturation of local hydrocarbon structures.

Calculated Level 1 Linear Models (P_g, P_{am} и P_s) were combined to obtain the model *Pk* by the equation (4):

$$P_k = \frac{P_g \cdot P_{am} \cdot Ps}{P_g \cdot P_{am} \cdot P_s + (1-P_g)\cdot(1-P_{am})\cdot(1-P_s)}, \quad (4)$$

$$clas = 78.6\ \%.$$

Regression analysis was performed on the obtained complex values of Pk to determine the influence of individual criteria on the probability of saturation of structures.

When building regression models, the approach of ranking the initial data from maximum to minimum values of *Pk* was used. The first model included the initial data for the first three ranked structures. At each subsequent step, one row of initial data is added, and the model is recalculated and analyzed. The addition of initial data rows occurs until the full study sample is accumulated. In each model, the coefficients of the individual criteria are calculated using the least squares method [29–44]. Figure 2 shows the coefficients of the individual criteria of the regression complex model (*C*). The figure shows that for saturated HC structures (*Pk* > 0.5 fractions of units), the main role in saturation is played by the accumulation criteria. It is also observed that in predicting empty structures, the generation criteria make a greater contribution relative to the other criteria, in the range

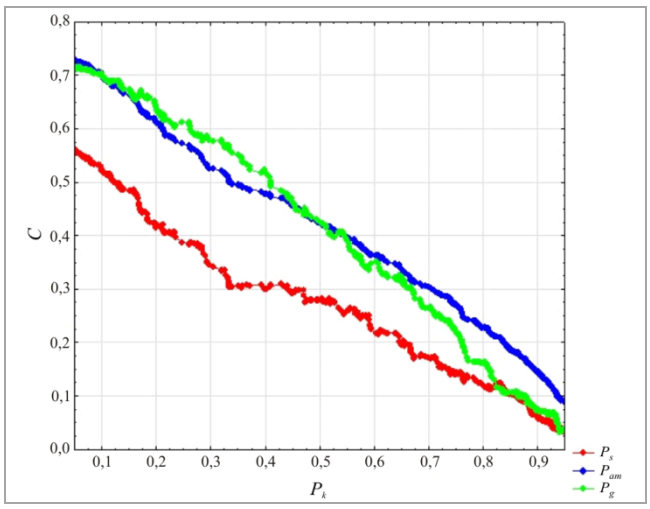

Fig. 2. Coefficients of individual criteria of regression complex models of level 2

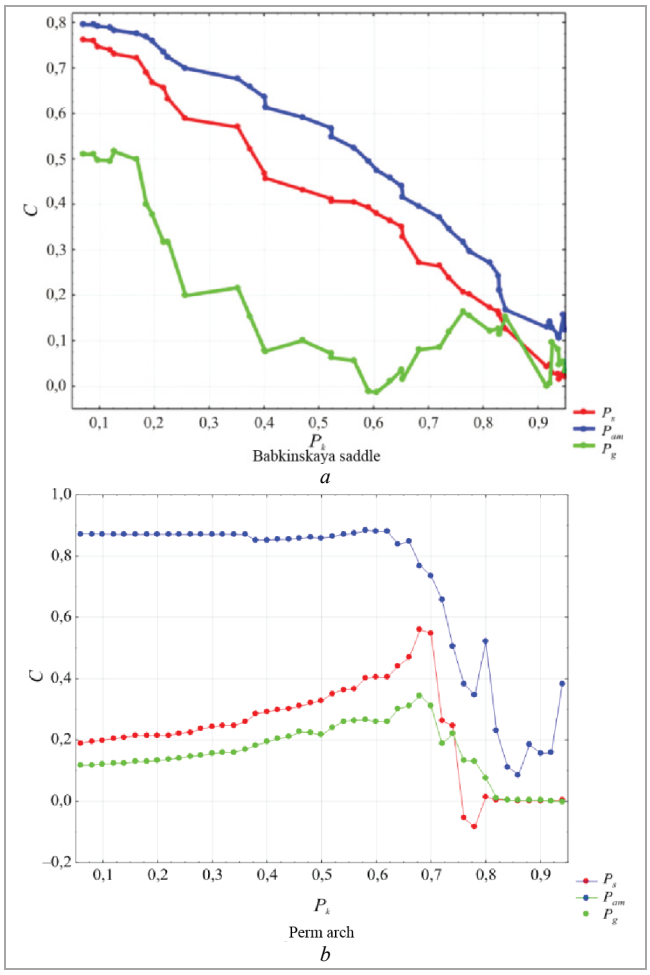

Fig. 3. Coefficients of individual criteria of Level 3 regression complex models for the Babkinskaya saddle (*a*) and Perm arch (*b*)

of P_k from 0.12 to 0.44 fractions of units, the values of P_g coefficients are higher than P_{am}. At the same time, the values of P_g and P_{am} coefficients do not diverge much from each other in this range. The criteria of deposit preservation over the whole range of probability P_k have the least influence in saturation of HC structures. A total of 708 models were calculated at level 2. The calculated correlation coefficient of regression models shows that empty structures are predicted better than saturated HC. The calculated Level 2 regression models poorly differentiate the contribution of

individual criteria to saturation of HC structures at different probability levels.

Level 2 models are calculated according to a set of criteria for the entire study area, but for more accurate forecasting it was decided to disaggregate the study area and build Level 3 models for each major tectonic element separately. The study area includes tectonic elements of the 1st order: Bashkirian arch (BA), Bymsko-Kungur monocline (BKM), Permian arch (PA), Verkhnekamsk depression (VKD) and Babkinskaya saddle (BaS).

For each large tectonic element, a complex probabilistic model was calculated according to formula (4), regression analysis was carried out with the gradual addition of initial data when ranking information by the P_k parameter, similar to the method of obtaining models at the 2nd level. The result of the construction of 729 regression models was the obtaining of coefficients of individual criteria of regression models for each tectonic element. Fig. 3 shows the coefficients of individual criteria of regression complex models of the 3rd level for the Bashkir and Permian arches.

Due to the large geological study of the Bashkirian arch, in which 365 out of 711 structures considered in the study are identified, the values of coefficients of individual criteria of the Bashkirian arch strongly influence the values of coefficients of regression complex models obtained at the 2nd level for the whole study area..

The criterion coefficients of the regression models constructed for the structures of the Babkinskaya saddle (the number of localized structures (N) is 54) are shown in Fig. 3, *a*. It is noticeable that the differentiation of the values of the coefficients of individual criteria differs from the coefficients obtained at the 2nd level. Accumulation criteria have the main influence on the saturation of the Babkinskaya saddle structures, while the generation criteria are inferior in importance to the conservation and accumulation criteria throughout the saturation probability. The significance of the influence of the preservation criteria is confirmed by the increased values of chlorine-bromine content (Cl_Br(Vk)) relative to the rest of the study area. The increased Cl_Br(Vk) content indirectly indicates the oil and gas content of the territory, which is due to the organic genesis of bromine in the waters of the visei associated with oil and gas formation.

From Fig. 3, *b*, it is noticeable that for the Permian arch (N=50) in the range of P_k from 0.05 to 0.75 fractions of units, the values of regression coefficients of the accumulation criterion have the greatest influence on the saturation of HC structures. Conservation criteria have a greater influence than generation criteria in the range of empty structures, which is associated with the increased water salinity in the Permian arch relative to other major tectonic elements involved in the study. High values of water mineralization indicate unfavorable conditions for preservation of deposits from physicochemical destruction. At P_k values equal to 0.75 fractions of units the influence of preservation criteria sharply decreases relative to generation criteria and is negative up to P_k values equal to 0.8 fractions of units. For structures saturated with HC (P_k range from 0.8 to 1.0 fractions of units), only accumulation criteria influence saturation.

A similar study was carried out for the VKD and BKM structures. In the territory of the Verkhnekamsk depression, the accumulation and generation criteria have the greatest influence on the saturation of structures, with the generation criteria having a greater influence than the accumulation criteria in the $P_k > 0.75$ range. The criteria of preservation over the whole probability range are inferior in the significance of the contribution. For the Bymsko-Kungur monocline it was noted that in the range of $P_k > 0.7$ the accumulation criteria make a smaller contribution to saturation of HC structures than the generation and preservation criteria. In the rest of the probability field the accumulation criteria have a greater influence on the of structures' saturation

It has been revealed that for all tectonic elements the greatest contribution is made by the accumulation criteria [45]. The coefficients of generation criteria by tectonic elements vary in the significance of their contribution to saturation of hydrocarbon structures, but they are consistently weaker than the accumulation criteria what generally confirms the previously obtained conclusions. The constructed models of the 3rd level proved that on the territory of the south of Perm Krai the forecast of oil and gas content of local structures should be carried out separately by tectonic elements. For tectonic elements due to different formation conditions, different criteria affect the saturation of structures with hydrocarbons differently.

Based on the results of all the above mentioned studies it was identified 15 forecast structures which turned out to be saturated with hydrocarbon, as well as 80 ones which turned out to be empty. The saturation of the identified structures is confirmed by the results of all studies at different levels.

Conclusion

Within the framework of the study, local structures of the 3rd order of Visean complex of sediments, which had not been drilled before, were identified. The criteria for the generation, accumulation and preservation of hydrocarbon deposits are analyzed, and individual statistical models are constructed. Individual statistical models made it possible to obtain complex models of the 1st level separately according to the criteria. These models are characterized by low predictive characteristics. Level 1 models were used to obtain Level 2 models that take into account a set of criteria for the entire study area. The regression analysis showed that the accumulation criteria have the greatest influence on the saturation of hydrocarbon structures. For each large tectonic element the models of the 3rd level were obtained and analyzed by regression method, which proved that it is most effective to forecast oil and gas content of local structures separately by tectonic elements taking into account the data on accumulation, generation and preservation of HC deposits. The result of all the studies was the identification of 15 potentially HC saturated structures that have not been previously drilled. This study will allow further more rational planning of geological and exploration works to search for oil deposits in the complex of Visean sediments.

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