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Using the Results of Differentiation and Grouping of Deposits to Solve the Problems of Developing Carbonate Reservoirs in the Volga-Ural Oil and Gas Province

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Использование результатов дифференциации и группирования залежей для решения задач разработки карбонатных коллекторов Волго-Уральской нефтегазоносной провинции

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carbonate reservoirs, field development, tectonic-stratigraphic confinement of objects, well stimulation, geological and statistical modeling, hierarchy analysis method, discriminant analysis, principal component method, control and regulation of oil production processes, monitoring of residual oil reserves, ranking of liquid hydrocarbon accumulation zones promising for development.

The relevance of the topic chosen for the study is due to the widespread need to solve development tasks within the framework of the implementation by the subsurface user of high-level monitoring and control of oil recovery processes in fields with a complex geological structure in order to make timely and effective management decisions. Using the complex results of differentiation and grouping of deposits in the Volga-Ural oil and gas province, confined to the carbonate reservoirs of the Lower Carboniferous system, the relevance of the parameters characterizing the key geological and physical characteristics of productive formations and saturating fluids was assessed. Using the hierarchy analysis method in the nonlinear system under study, formed after calculating the percentage of correctly grouped objects and the values of the main components, a rating of potential N field parts containing residual oil reserves promising for involvement in the drainage and development process was formed. By calculating the priority vector for both one of the parameters and for their combination with each other, qualitative results were obtained that make it possible to effectively build a strategy to increase the oil recovery coefficient by taking into account the hierarchy level of the six main indicators when planning or modeling the design of geological and technical measures, including in specialized software. This, in turn, leads to the formation of an alternative view on the study of the degree of mutual influence of the main geological and physical characteristics of productive formations with each other under various boundary conditions formed as a result of continuous processes in the borehole-formation system. The objectivity of the revealed patterns has been successfully confirmed within the framework of point comparison and comparison with the available results of geophysical and hydrodynamic studies of wells, screening and analysis of key technological parameters for the development of liquid hydrocarbon deposits, which significantly increases the scope of the results in solving the problems of developing mature fields.

Ключевые слова:
карбонатные коллекторы, разработка месторождений, тектонико-стратиграфическая приуроченность объектов, геолого-технические мероприятия, геолого-статистическое моделирование, метод анализа иерархии, дискриминантный анализ, метод главных компонент, контроль и регулирование процессов нефтеизлечения, мониторинг остаточных запасов нефти, ранжирование перспективных для разработки зон скопления жидких углеводородов.

Актуальность выбранной для исследования темы обусловлена повсеместной необходимостью решения задач разработки в рамках реализации недропользователем высокоуровневого мониторинга и контроля процессов нефтеизвлечения на месторождениях со сложным геологическим строением для принятия своевременных и эффективных управленческих решений. При помощи комплексных результатов дифференциации и группирования залежей Волго-Уральской нефтегазоносной провинции, приуроченных к карбонатным коллекторам нижнекаменноугольной системы, проведена оценка релевантности параметров, характеризующих ключевые геолого-физические характеристики продуктивных пластов и насыщающих их флюидов. С использованием метода анализа иерархии в исследуемой нелинейной системе, образуемой после расчета процента правильно сгруппированных объектов и значений главных компонент, сформирован рейтинг потенциальных для разработки участков залежей месторождения N, содержащих в себе перспективные для вовлечения в процесс дренирования и освоения остаточные запасы нефти. При помощи расчетов вектора приоритетов как для одного из параметров, так и для их совокупности между собой получены качественные результаты, позволяющие эффективно выстроить стратегию повышения коэффициента нефтеизвлечения за счет учета уровня иерархии шести основных показателей при планировании или моделировании дизайна геолого-технических мероприятий, в том числе в специализированных программных обеспечениях. Это, в свою очередь, приводит к формированию альтернативного взгляда на изучение степени взаимовлияния основных геолого-физических характеристик продуктивных пластов между собой при различных граничных условиях, образуемых в результате протекания непрерывных процессов в системе «скважина – пласт». Объективность выявленных закономерностей успешно подтверждена в рамках точечного сравнения и сопоставления с имеющимися результатами геофизических и гидродинамических исследований скважин, скрининга и анализа ключевых технологических параметров разработки залежей жидких углеводородов, что существенно повышает область применения результатов в рамках решения задач разработки зрелых месторождений.

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Introduction

The instability of nonlinear processes in the study of complex technological systems of the oil and gas industry imposes a number of difficulties in their analysis by various approaches [1–7]. This leads to the formation of unfounded and unrepresentative conclusions regarding the current state of facilities development and possible prospects for increasing well productivity improving and regulating waterflooding processes. In the context of a significant expansion of the recoverable resource base of the Russian Federation due to the exploration of reserves confined to low-permeability and heterogeneous reservoirs it arises a list of issues the solution of which is associated with various types of risks which affect the efficiency of managerial decision-making. Formation of the necessary strategy for the development and commissioning of hard-to-recover reserves should be carried out, first of all, with the use of integrated scientific and methodological foundations making it possible to successfully select the necessary list of tools for modeling various production processes within the framework of proactive resource management [8–13].

On the basis of the obtained empirical and theoretical results it is not always possible to give an objective and highly qualified assessment of oil and gas facilities under consideration, which leads to:

- additional costs of resources for the refinement of existing models through a series of field tests and experiments;
– the use of facilities without sufficient by the quantitative and qualitative ratio of the evidence and argumentation base [14–16];
– obtaining various errors in modeling processes and systems located at a lower level of the hierarchy;
– development of scale invariance of spatial and temporal characteristics of facilities [17–19];
– low level of information content of data from the point of view of practical value and the possibility of using them in solving key problems of field development.

In this regard, at the present stage of liquid hydrocarbon production, a significant role is given to the search, refinement and expansion of the scope of application of models obtained in the framework of applied research, which is caused by the need to implement high-quality support and regulation of fluid movement processes to the bottoms of producing wells [20–23].

Materials and methods

One of the most commonly used tools for reducing the dimensionality of the problem and establishing certain correspondences between input and output signals is the integrated analysis of field data using geological and statistical modeling [24–27]. For example, methods based on pattern recognition theory are of considerable interest, which make it possible to successfully classify facilities in conditions of poorly defined processes, fuzzy constraints, and low information density using representations of parameters in the form of *n*-dimensional vectors, each of which affects the final result. At the same time, taking into account the specifics of the oil industry and the implementation of its technological processes, a significant number of them form systems of complex inequalities, the solution of which is not always possible to realize based only on the relevant information obtained [28–31].

The insufficient level of reliability of estimates of geological and physical parameters based on the results of field or laboratory tests contributes to reduction in the managerial decision-making effectiveness, which directly influence the results of measures aimed at improving well productivity, optimizing downhole pumping equipment and, in general, successfully implementing oil production processes [32]. To solve the current problem within the framework of clarifying the results of geological and statistical modeling, an important aspect is to determine the parameters which have a significant impact on the level of distribution of facilities in the axes of canonical discriminant functions, the distance between the centroids of the groups and the density of each of them relative to each other.

The above mentioned confirms the necessity to search for an optimal approach to the problem of maximum use of information on the degree of belonging facilities to a particular group to solve the problems of developing complex geological structures [33–35]. In particular, the most promising for development at the present stage of oil production are carbonate reservoirs of the Volga-Ural oil and gas province (VUOGP) which have the following characteristics:

– complex and heterogeneous structural architecture in symbiosis with a nonlinear sedimentation cycle [36];
– branched micro- and macrofractures of rocks;
– significant heterogeneity of changes in filtration and capacitive characteristics under the constant or variable influence of reservoir conditions;
– a high degree of rock deformation, which contributes to a change in the direction of fluid movement in fractured media and, as a result, the formation of uncertainty zones during numerical or hydrodynamic modeling [37–40].

Results

In the course of discriminant analysis on data of 18 groups of deposits confined to carbonate reservoirs of VUOGP it is constructed a diagram of the distribution of each of the parameters under consideration contribution to the percentage of correctly grouped objects (Fig. 1).

As it can be seen, the selected parameters determine up to 80 % of identifiability, and the contribution of the parameter m_g is numerically equal to the sum of the contributions of the parameters: m_k, r_n, Rnas, G, Rpl. A different situation is observed, for example, in the study of the Lower Carboniferous and Upper Devonian systems of VUOGP [41-43]. The discriminant analysis carried out for 6 groups and 16 parameters determined that 9 parameters provide 80 % of identifiability, moreover their order differs significantly from the previous case (Fig. 2).

On the basis of the research results we will identify that the application of discriminant analysis makes possible to carry out only the upper-level evaluation of parameters within the considered system, its boundary conditions and indicators, which does not always give positive results while forming the algorithm of residual oil reserves involvement into development. This is associated, for example, with high correlation between geological and physical characteristics of objects, which varies significantly within a particular stratigraphic complex [44-46].

In this case, an objective and correct classification of the parameters according to a number of different criteria, necessary for the existing models refinement and expansion of the scope of their application, can be carried out by the method of analysis of hierarchy (MAH). This method allows an objective and relevant evaluation of the parameters of an unstable system [47]. The advantage of MAH in solving problems of liquid hydrocarbon field development is the ability to work with heterogeneous data by decomposing them into interrelated clusters.

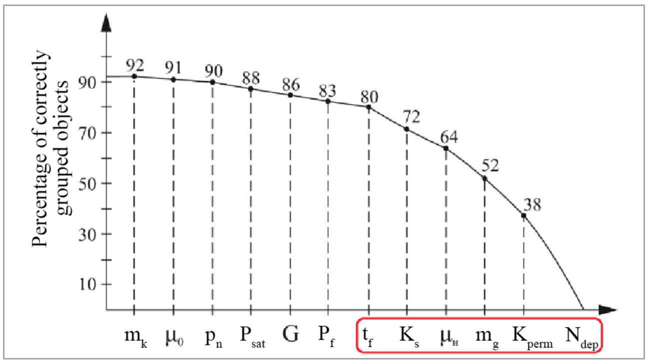

Fig. 1. Contribution of parameters to the percentage of correctly grouped VUOGP objects in carbonate reservoirs: m_k – average porosity value (by core), %; μ_0 – relative viscosity of oil; p_n – density of formation oil, kg/m^3; P_{sat} – pressure of oil saturation with gas, MPa; G – formation gas factor, m^3/t; P_f – formation pressure, MPa; t_f – formation temperature, °C; K_s – oil saturation factor, fractions of units; μ_n – viscosity of formation oil, mPa·s; m_g – average porosity value (according to geophysics), %; K_{perm} – permeability coefficient, 10^{-3}, μm^2; H_{dep} – depth of formation, m

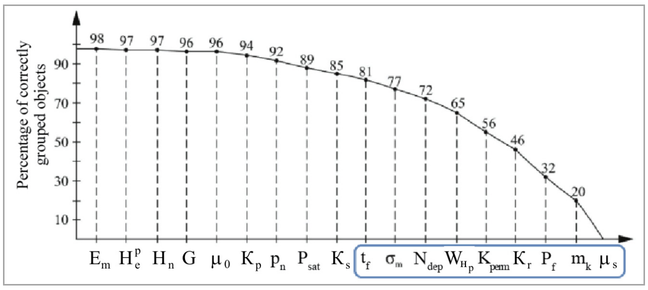

Fig. 2. Parameter contributions to the percentage of correctly grouped VUOGP objects in carbonate reservoirs of the Lower Carboniferous and Upper Devonian systems: E_m – entropy of porosity; H_e^p – average value of the effective oil saturated thickness in the drilling zone, m; N_p – average value of thickness of oil-saturated layers, m; K_p – the share of reservoir rocks in the total thickness of the reservoir, decimal units; σ_m – standard deviation of porosity, %; W_{H_p} – variation in the thickness of oil-saturated layers, %; K_r – reservoir dissection factor

The initial data for calculations stood in:

• criteria:

– ranked series of parameters, providing up to 80 % identifiability of objects at implementing discriminant analysis, calculated by the formula (1):

$$J = \frac{\sum_{i=1}^{n} \frac{R_i}{n}}{n}, \qquad (1)$$

where J – informativeness of this or that parameter in determining the percentage of correctly grouped objects; R_i – parameter rank number in the i-th variant of grouping the objects; n – the number of grouping options in which the parameter was included;

• alternatives:

– deposits in carbonate reservoirs of the VUNGP coal system, including the most promising areas for geological and technical measures (GTM) based on the results of monitoring, screening and analysis of geological and field data of the N field, confined to the Blagoveshchenskaya Depression (BD):

– Verey horizon (Vr), ciphers of experimental plots (1XV-5XV);

– Bashkirian tier (Bsh), ciphers of experimental plots (1XVI-4XVI);

– Kashira horizon (Ksh), ciphers of experimental plots (1XII-6XII);

– Podolsk horizon (Pd), ciphers of experimental plots (1VII-3VII).

To determine the priority level of the criteria under consideration, we use the matrix of pairwise comparisons obtained by expert evaluation and analysis of the results of various geological and engineering operations over the last year for the object of study. Then, based on the obtained values, we calculate the indicators of local priority vectors (Table 1) using formula (2):

$$\omega_i = \frac{\vartheta_{(1-6)_i}}{\sum \vartheta_{(1-6)}}, \qquad (2)$$

where ω_i – value of the local vector of the i-th criterion; $\sum \vartheta_{(1-6)}$ – sum of intermediate evaluations of criteria; $\vartheta_{(1-6)_i}$ – intermediate assessment of the i-th criterion, calculated according to the formula:

$$\vartheta_{(1-6)_i} = \sqrt[6]{\vartheta_{1i} \cdot \vartheta_{2i} \cdot \vartheta_{3i} \cdot \vartheta_{4i} \cdot \vartheta_{5i} \cdot \vartheta_{6i}}, \qquad (3)$$

where $\vartheta_{1_i}, \vartheta_{2_i} \ldots \vartheta_{6i}$ – assessment of the criteria importance for each of the i-th parameter.

To check the objectivity of expert assessments, a system (4) is consistently solved, on the basis of which the consistency of the results and the absence of contradictions are established:

$$\begin{cases} \partial = \dfrac{|\alpha_{\max} - n|}{n-1}; \\ \alpha_{\max} = \sum_{i=1}^{1} \varpi_i \cdot \omega_1 + \sum_{i=2}^{2} \varpi_i \cdot \omega_2 + \sum_{i=3}^{3} \varpi_i \cdot \omega_3 + \\ + \sum_{i=4}^{4} \varpi_i \cdot \omega_4 + \sum_{i=5}^{5} \varpi_i \cdot \omega_5 + \sum_{i=6}^{6} \varpi_i \cdot \omega_6; \\ \chi_i = \dfrac{\partial}{\tau_i} > 0,1, \end{cases}$$

where ∂ – consistency index; $\alpha_{\max}$ – the range of expert assessments; n – dimensionality of the matrix of expert assessments (see columns 2–7 of Table 1); $\sum_{i=1}^{6} \varpi_i$ – sum of assessments of the i-th column of the matrix; χ_i – parameter, characterizing the consistency ratio of i-criteria; τ_i - value of random consistency variable.

The final stage of the analysis is represented by the calculation of global priority *ki* indicators based on the initial data sample (formula (5)), on the basis of which the rating of involvement in development of the most promising areas of the considered deposits of the N field, confined to the carbonate reservoirs of the VNUGP, is formed (Table 2):

$$k_i = \sum_{i=1}^{6} \omega_i \cdot \xi_i, \qquad (5)$$

where k_i – global priority of the i-th criterion; ξ_i – vectors of priorities of the studied deposit areas.

According to the results of the rating, area 1XV of the N field, confined to the Blagoveshchenskaya depression of the Verey horizon, is recommended as the most promising for involvement in development of residual oil reserves by means of a number of geological and technical measures.

Table 1

Results of criteria importance assessment in the conditions of VUOGP deposits confined to carbonate reservoirs

Parameter number	1	2	3	4	5	6	7	8
	ϖ_i							
Criterion	K_p	K_{perm}	μ_s	m	H_e	K_s	$\vartheta_{(1-6)_i}$	ω_{1-6}
K_p	1	9	8	6	4	3	4.1602	0.455
K_{perm}	$\frac{1}{9}$	1	$\frac{1}{8}$	$\frac{1}{3}$	$\frac{1}{5}$	$\frac{1}{6}$	0.2316	0.0253
μ_s	$\frac{1}{8}$	8	1	3	$\frac{1}{2}$	$\frac{1}{3}$	0.8908	0.0974
m	$\frac{1}{6}$	3	$\frac{1}{3}$	1	$\frac{1}{4}$	$\frac{1}{8}$	0.416	0.0453
H_e	$\frac{1}{4}$	5	2	4	1	$\frac{1}{2}$	1.3076	0.143
K_s	$\frac{1}{3}$	6	3	8	2	1	2.1398	0.234
Sum	1.986	32	14.458	22.3	7.95	5.125	9.146	1

Table 2

Rating of the most promising for engagement in the development of VUOGP deposits of the N field

Code of the i-th section of the deposit	Priority vectors ξ_i						Rating, k_i
	K_p	K_{perm}	μ_s	m	H_e	K_s	
1XV BW (Vr).	**0.554***	0.323	**0.289**	0.122	0.321	0.123	**0.368** (1)
4XVI BW(Bsh)	0.098	**0.467**	0.109	0.167	**0.404**	0.147	0.166 (4)
3XII BW(Ksh)	0.126	0.387	0.98	**0.188**	0.087	0.212	0.233 (3)
1VII BW(Pd)	0.321	0.454	0.067	0.119	0.039	**0.321**	0.243 (2)

Note: the highest priority values for the various geological and physical parameters are indicated in bold.

In turn, section 4XVI of the Bashkir horizon has less potential for effective development of liquid hydrocarbon resources, which is confirmed by the following factors:

– rather high values of priority vectors for permeability parameters and effective oil saturated thickness;

– results of hydrodynamic modeling, geophysical well tests and forecast calculations [48];

– analysis of dynamics of changes in productivity of producing wells.

The rest areas of the VUOGP deposits of the N field have ratings, the values of which do not exceed 0.05 units, which, in turn, requires a more detailed and comprehensive analysis at the microlevel of the organization of nonlinear oil production systems with the involvement of versatile information on reservoir processes.

Conclusion

As a result of using the hierarchy analysis method for a set of geological and physical parameters characterizing the reservoir properties of reservoirs and fluids saturating them, the following conclusions were made for the VUOGP deposits confined to carbonate reservoirs:

– clarification of the results of discriminant analysis makes it possible to identify a number of parameters that have a prevailing influence on the success of further operations related to various aspects of modeling or operations of planning geological and technical measures;

– by calculating six priority vector values depending on the deposit areas, the most important parameters were determined both separately for each of them and in the aggregate, which made it possible to form a rating of the most promising zones for involvement of residual reserves;

– the regularities obtained during the study are confirmed by the results of the analysis of geological and field data of the N field operation, geophysical and hydrodynamic studies of wells.

In order to ensure the most rational conditions for the development of the object of the investigation it is necessary to conduct similar and more detailed studies in order to search for and assess the opportunities of increasing the oil recovery factor.

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