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Development of a Geological and Statistical Approach to the Justification of an Analogue Field for a Structure Prepared for Deep Drilling by 3D Seismic in the Perm Krai

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Разработка геолого-статистического подхода к обоснованию месторождения-аналога для структуры, подготовленной к глубокому бурению сейсморазведочными работами МОГТ 3D в Пермском крае

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When developing design documentation for geological exploration, which includes the rationale for laying a prospecting and appraisal well in order to search for and evaluate oil deposits in geological structures, there is a need to identify an analogue field characterized by a similar geological structure.
In this regard, there is a need to develop an up-to-date geological and statistical approach that makes it possible to most accurately determine an analogue field based on geological and statistical data.
This article discusses the geological-statistical method, which not only confirms the nature of the correspondence of structural plans in general, but also allows us to differentiate areas with different geological and structural structures, characterized by different degrees of correspondence of structural plans within the area, that studied by 3D seismic exploration.
The nature of the influence significance of the indicators OG S, OG IK, OG IP, OG IIK and OG III on OG IIP, determined as a study result, confirmed the correspondence between structural plans of the Lower Carboniferous System (OG IK, IP, IIK, IIP) and inconsistency between structural plans of Permian (OG S) and Devonian terrigenous deposits (OG III).
To determine the analogue field of the geological structure, a discriminant analysis was carried out on groups of wells, the correspondence and belonging of which to different deposits was confirmed by a regression study.

Ключевые слова:
амплитуда структуры, геолого-разведочные работы, подтверждаемость структур глубоким бурением, оценка рисков, отражающий горизонт, геолого-статистический анализ, дискриминантный анализ.

При разработке проектной документации для проведения геолого-разведочных работ, включающей в себя обоснование заложения поисково-оценочной скважины с целью поиска и оценки залежей нефти в геологических структурах, возникает необходимость определения месторождения-аналога, характеризующегося схожим геологическим строением.
В связи с этим появляется потребность разработки актуального геолого-статистического подхода, позволяющего наиболее точно определить месторождение-аналог на основе геолого-статистических данных.
Рассматривается геолого-статистический метод, который не только подтверждает характер соответствия структурных планов в целом, но и позволяет дифференцировать участки с различным геолого-структурным строением, характеризующиеся разной степенью соответствия структурных планов в пределах площади, изученной сейсморазведочными работами МОГТ 3D.
Характер значимости влияний показателей ОГ S, ОГ $I^К$, ОГ $I^П$, ОГ $II^К$ и ОГ III на ОГ $II^П$, определенный в результате исследования, подтверждает соответствие структурных планов нижнего отдела каменноугольной системы (ОГ $I^К$, $I^П$, $II^К$, $II^П$) между собой и несоответствие их структурным планам пермских (ОГ S) и девонских терригенных отложений (ОГ III).
Для определения месторождения-аналога геологической структуры был проведен дискриминантный анализ по группам скважин, соответствие и принадлежность которых к разным месторождениям подтверждены регрессионным исследованием.

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Introduction

When developing project documentation for geological exploration works, which includes justification of a prospecting and appraisal well for the purpose of search and evaluation of oil deposits in geological structures, there is a need to identify the ideal analogous field characterised by a similar geological structure [1–12].

In this connection there appeared the necessity to develop an actual geological and statistical approach which allows determining the ideal analogue on the basis of geological and statistical data in the most accurate way.

Statistical Differentiation of Wells According to the Principle of Relation to Different Geological Exploration Areas

To define the analogue field, a stepwise multiple regression was performed in Statistica software for groups of different numbers of exploration wells *n* drilled in the geological exploration area under consideration as well as in the adjacent areas. The regression was performed for *n* from 3 to 27 ea. inclusive. The sample was ranked in ascending order of the OG IIP absolute mark [10–24].

The results of the regression study is presented in Table 1. Statistically significant indicators, for which the value of p-criterion characterising the probability of error of the first kind (i.e. the probability of randomness of the obtained result) is less than or equal to 0.05, are highlighted in bold. The value of the multiple correlation coefficient R2, which characterises the closeness of linear dependence of one variable on other variables, begins to increase in the range *n* from 3 to 9, further, at *n* from 10 to 27 the value of the coefficient reaches its maximum of 0.997–0.999 and practically does not change. The gradual increase of the coefficient is explained by the fact that the more values of variables are used in the analysis, the more accurately the regression equation is described and, as a consequence, the stronger the relationship between the dependent and independent variables.

The standard error SE indicates how much the sample mean may differ from the parent universe mean. The statistical model is applicable to the considered geological structure "S" because the maximum standard error encountered in the regression analysis in the range of *n* from 19 to 27 is 5.30 m, and the amplitude of the structure "S" on the OG IIP is equal to 14 m.

In the range of *n* from 27 to 19 the model is controlled by statistically significant OG II^k and OG I^P.

The magnitude of the standard error *SE* in this range gradually increases from 4.52 to 5.30 m. The multiple correlation coefficient R^2 vary in the value of 0.998.

This model confirms that the wells involved belong to field “A”.

The first restructuring of the model is observed in the range n from 18 to 13: the model continues to be controlled by statistically significant indicators of the OG II^k and OG I^P, and the OG-I^k indicator also begins to have a statistically significant effect on the model.

The magnitude of standard error *SE* in this range gradually increases from 3,64 to 3,93 m. The multiple correlation coefficient R^2 vary in the value of 0.999.

This model confirms that the wells involved belong to field “B”.

The second restructuring of the model is observed in the range *n* from 12 to 10: the model continues to be controlled by statistically significant indicators of OG I^P and OG I^k.

The magnitude of standard error *SE* are in the range from 3,53 to 3,85 m. The multiple correlation coefficient R^2 vary in the value of 0.998.

This model confirms that the wells involved belong to field “C”.

The third restructuring of the model is observed in the range *n* from 9 до 8: The model continues to be controlled by a statistically significant OG I^P, the influence of the OG I^k indicator is weakening.

Table 1

Results of the regression analysis

Field	*n*, ea.	Free member	Coefficients for indicators, dec.units					R^2, dec.units	*p*-criterion, dec.units	*SE*, m
			OG S	*OG I^K*	*OG I^P*	*OG II^K*	*OG III*			
“D”	3	–2630,30	–0,06		–1,07					
	4	–2073,05	–0,02		–0,61	0,05				
	5	**–1481,18**	0,04					0,693	0,194592	1,314
	6	**–1215,69**	0,05		0,25			0,783	0,240577	1,388
	7	–699,373	0,071	0,779				0,829	0,098265	2,206
	8	146,611			**1,075**		0,250	0,798	0,079233	3,037
	9	713,295			**1,493**		0,313	0,966	0,000308	3,178
“C”	10	796,744		**–2,098**	**3,275**		0,461	0,997	2,76E^{-08}	3,530
	11	464,455		**–1,780**	**2,962**		0,306	0,998	6,43E^{-10}	3,793
	12	504,928		**–1,682**	**2,870**		0,325	0,998	1,79E^{-11}	3,850
“B”	13	–22,225		**–1,131**	**2,188**	0,219		0,999	4,93E^{-13}	3,774
	14	–7,070		**–1,162**	**2,192**	0,249		0,999	1,26E^{-14}	3,641
	15	40,114		**–1,106**	**1,983**	**0,397**		0,999	1,26E^{-15}	3,927
	16	30,805		**–1,081**	**1,975**	**0,379**		0,999	3,99E^{-17}	3,808
	17	36,436		**–1,073**	**1,946**	**0,399**		0,999	1,14E^{-18}	3,679
	18	34,503		**–1,036**	**1,898**	**0,407**		0,999	3,32E^{-20}	3,567
“A”	19	**85,053**	–0,086		**0,298**	**0,915**		0,998	7,6E^{-19}	5,297
	20	**94,193**	–0,085		0,271	**0,941**		0,998	3,96E^{-20}	5,235
	21	**91,669**	–0,086		**0,277**	**0,935**		0,998	1,63E^{-21}	5,098
	22	**92,963**	–0,092		**0,275**	**0,939**		0,998	7,19E^{-23}	4,986
	23	**93,478**	–0,094		**0,276**	**0,938**		0,998	2,94E^{-24}	4,867
	24	**92,954**	–0,094		**0,278**	**0,936**		0,998	1,18E^{-25}	4,750
	25	**91,558**	–0,093		**0,280**	**0,935**		0,998	5,09E^{-27}	4,654
	26	**95,399**	–0,094		**0,266**	**0,947**		0,998	2,76E^{-28}	4,611
	27	246,681	–0,090		**0,257**	**0,930**	0,089	0,998	3,65E^{-28}	4,515

Table 2

Qualitative characteristics of discriminant analysis

n = 23	Wilkes lambda, dec.units	Particular lambda, dec.units	*F*-criterion – (3.18)	*p*-criterion, dec.units	Tolerance	R^2
OG I^K	0,002	0,189	25,780	0,000	0,642	0,358
OG S	0,005	0,068	81,908	0,000	0,291	0,709
OG III	0,006	0,063	88,912	0,000	0,133	0,867
OG $I^П$	0,003	0,134	38,713	0,000	0,119	0,881

Table 3

Posteriori probabilities

N	Group	Posteriori probabilities			
		Group “A” (p = 0,36)	Group “B” (p = 0,24)	Group “C” (p = 0,12)	Group “D” (p = 0,28)
3	«D»	0,000	0,000	0,000	1,000
4	«D»	0,000	0,000	0,000	1,000
5	«D»	0,000	0,000	0,000	1,000
6	«D»	0,000	0,000	0,000	1,000
7	«D»	0,000	0,000	0,000	1,000
8	«D»	0,000	0,000	0,000	1,000
9	«D»	0,000	0,000	0,000	1,000
10	**«S»**	**0,000**	**0,000**	**0,000**	**1,000**
11	«C»	0,000	0,000	1,000	0,000
12	«C»	0,000	0,000	1,000	0,000
13	«C»	0,000	0,000	1,000	0,000
14	«B»	0,000	1,000	0,000	0,000
15	«B»	0,000	1,000	0,000	0,000
16	«B»	0,000	1,000	0,000	0,000
17	«B»	0,000	1,000	0,000	0,000
18	«B»	0,000	1,000	0,000	0,000
19	«B»	0,000	1,000	0,000	0,000
20	«A»	1,000	0,000	0,000	0,000
21	«A»	1,000	0,000	0,000	0,000
22	«A»	1,000	0,000	0,000	0,000
23	«A»	1,000	0,000	0,000	0,000
24	«A»	1,000	0,000	0,000	0,000
25	«A»	1,000	0,000	0,000	0,000
26	«A»	1,000	0,000	0,000	0,000
27	«A»	1,000	0,000	0,000	0,000
28	«A»	1,000	0,000	0,000	0,000

The value of the standard error SE in this range gradually decreases from 3.46 to 3.04 m. The multiple correlation coefficient R^2 gradually decreases from 0.983 to 0.798.

This model confirms that the wells involved in it belong to field D.

There are no statistically significant values in the range of n from 7 to 3, which is associated with the small number of n used in multiple regression. The wells involved in this model were drilled within field D.

There is a different dependence of the structural plan of the OG II^P on the indicators of OG S, OG I^K, OG I^P, OG $II^k$and OG III in different n ranges. Moreover, this makes it possible to group areas that obey similar geological and statistical models (similar in the nature of the influence of significant indicators). The significant influence of the indicators OG I^K, OG I^P, and OG II^k on OG II^P and the insignificant influence of OG S and OG III indicators on OG II^P confirms the correspondence of the structural plans of the lower part of the Carboniferous system (OG I^K, I^P, II^K, II^P) with each other and their discrepancy with the structural plans of the Permian (OG S) and Devonian terrigenous deposits (OG III) [25–34].

Probabilistic and Statistical Substantiation of Analogue Field

To determine the field-analogue of the geological structure "S", a discriminant analysis was carried out based on the results of a regression study [34–46]. Discriminant analysis was carried out for groups of wells, the correspondence and belonging of which to different fields with different types of structural plan ratios was confirmed by regression studies. In total, there are four groups of wells assigned to different fields: "A", "B", "C" and "D". The qualitative characteristics of the discriminant analysis based on the known values of the four groups are presented in Table 2.

Wilkes' lambda, which characterizes the ratio of intragroup variability to general variability and determines the quality of grouping, in this case is quite small and ranges from 0.002 to 0.006 parts of units, which means that the groups are homogeneous within themselves and practically do not intecross with each other.

The partial lambda determines the value of a particular classification feature, i.e. determines the degree of variability of the Wilkes lambda (the degree of variability of intragroup homogeneity) after the addition of a variable. That is, the lower its value, the more valuable the feature is. In this case, the most valuable variables are OG S and OG III, since they are not as widespread as they are compared to OG I^P.

The *F*-criterion determines the variability of variances as a result of excluding this or that feature from the analysis, and the *p*-criterion determines the level of its statistical significance, i.e. the probability that the result will be random. If the exclusion of a feature leads to a statistically significant change in the variance ratio, then this condition makes an important contribution to the discrimination of groups.

Tolerance determines the redundancy of the feature, that is, the lower it is, the stronger this feature is associated with all the rest. The coefficient of multiple correlation R^2, on the contrary, determines the degree of interrelation of a feature with the others used in the model.

The canonical discriminant functions determining the classification process were subject to laws:

$$Root\,1 = -4{,}414 - 4{,}880\left(OG\,\mathrm{I}^{k}\right) - 9{,}362\left(OG\,S\right) - 19{,}436\left(OG\,\mathrm{III}\right) + 3{,}290\left(OG\,\mathrm{I}^{P}\right);$$

$$Root\,2 = -2{,}806 + 4{,}442\left(OG\,\mathrm{I}^{k}\right) - 71{,}492\left(OG\,S\right) - 26{,}153\left(OG\,\mathrm{III}\right) + 4{,}589\left(OG\,\mathrm{I}^{P}\right);$$

$$Root\,3 = 1{,}123 + 0{,}727\left(ОГ\,\mathrm{I}^{k}\right) + 21{,}528\left(ОГ\,S\right) - 9{,}771\left(ОГ\,\mathrm{III}\right) + 0{,}517\left(ОГ\,\mathrm{I}^{P}\right).$$

Graphs of the discriminant functions Root 1, Root 2 and Root 3 are presented in Fig. 1-3.

The eigenvalues of the roots of the functions Root 1, Root 2 and Root 3, characterising the quality of differentiation, are 40.66, 23.32 and 1.70, respectively. It means that the most representative in this case will be the graph of the roots of discriminant functions Root 1 and Root 2, because the greater the eigenvalue of the function, the more effective the differentiation.

Wells of group "A" are located only in negative values of Root 1 and Root 3 and only in positive values of Root 2. As can be seen from the previously constructed geological and statistical model corresponding to field "A", OG II^{P} is controlled by statistically significant indicators of OG II^{K} and OG I^{P}.

Wells of group "B" are located only in positive values of Root 1, Root 2 and Root 3. As can be seen from the previously constructed geological and statistical model corresponding to field "B", OG II^{P} is controlled by statistically significant values of OG II^{K} and OG I^{P} and OG I^{K}.

Group "C" wells are located only in positive values of Root 1 and only in negative values of Root 2 and Root 3. As can be seen from the previously constructed geological and statistical model corresponding to field "C", OG II^{P} is controlled by statistically significant indicators of OG I^{P} and OG I^{K}.

Wells of group "D" are located only in negative values of Root 1 and Root 2 and in both positive and negative values of Root 3. As can be seen from the previously constructed geological and statistical model corresponding to field "D", OG II^{P} is controlled by the statistically significant indicator of OG I^{P}.

A posteriori probabilities obtained as a result of discriminant analysis, characterising the probability of belonging of structure "S" to a particular group ("A", "B", "C" or "D") are presented in Table 3.

The scheme of joint distribution of posterior probabilities for the four groups under study, obtained by discriminant analysis, is presented in Fig. 2.

A regular distribution of groups of wells confined to different territories with different degrees of structural plan conformity has been defined. In the southern part the field "C" is located; three wells were drilled within its boundaries. To the North of the "C" field is the "B" field, with six wells drilled within its boundaries. Field A is located in the western part of the territory and nine wells have been drilled within its boundaries. In the north-eastern part of the territory there is field "D". Nine wells were drilled within its boundaries.

The aposteriori probability that the geological structure "S" belongs to the territory of the "D" deposit is 100 %. This means that the "D" field is the analogue for the "S" structure.

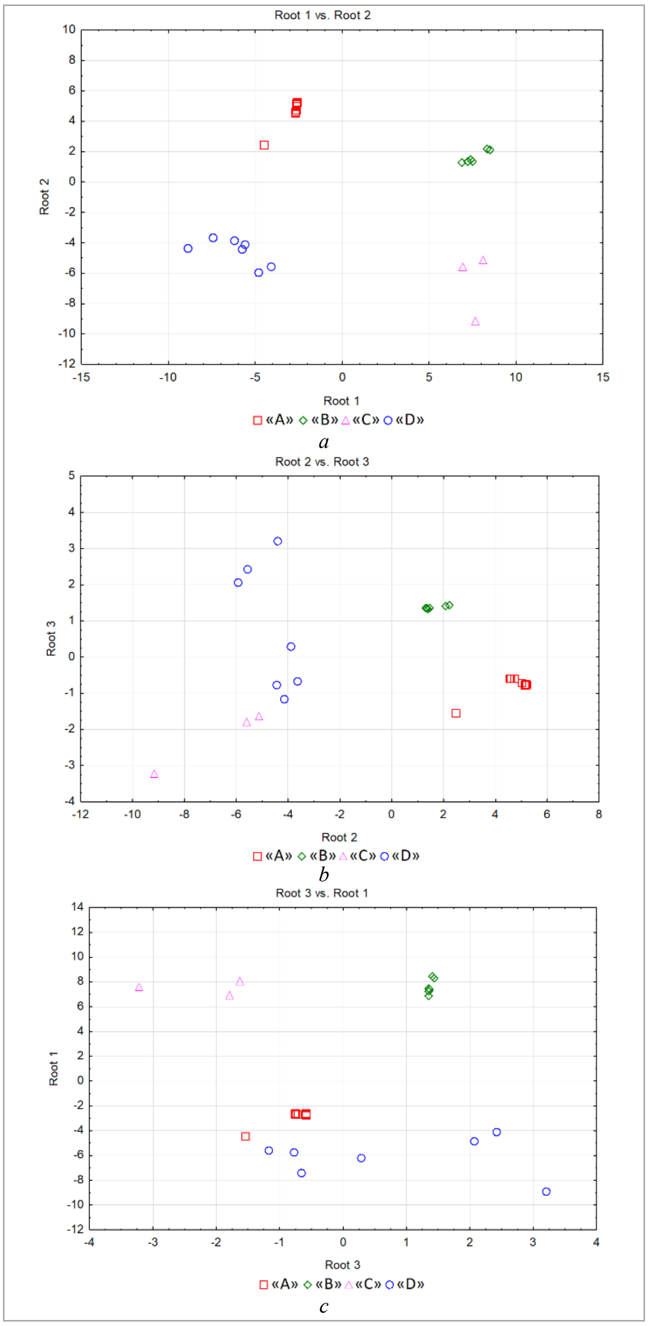

Fig. 1. Graph of the roots of discrinminant functions: *a* – Root 1 and Root 2; *b* – Root 2 and Root 3; *c* – Root 1 and Root 3

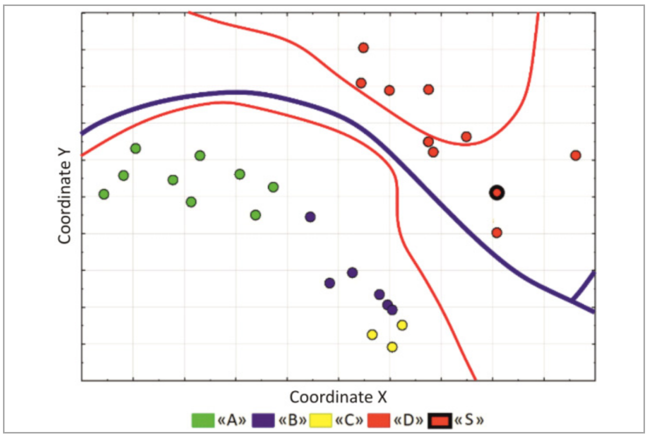

Fig. 2. Scheme of joint distribution of aposteriori probabilities for different groups; Blue – the boundaries of the tectonic elements of the first order, red – the second order

Conclusion

The results of the regression study made it possible to combine the obtained geological and statistical models, which are close in the nature of the influence of significant indicators, which, in turn, confirmed the belonging of different groups of wells to different fields.

The nature of significance of the influence of the indicators OG S, OG I^K, OG I^P, OG II^K and OG III on OG II^P, determined by the regression study, confirms the correspondence of the structural plans of the lower part of the coal system (OG I^K, IP, II^K, II^P) among themselves and their inconsistency with the structural plans of the Permian (OG S) and Devonian terrigenous sediments (OG III).

By the results of the statistical method based on the differentiation of areas with different geology and structure, characterised by different degrees of conformity of structural plans within the area under consideration of MOGT 3D seismic surveys, the analogue for the geological structure "S" was determined and statistically substantiated – the deposit "D".

References

1. Galkin S.V. Veroiatnostnyi prognoz geologicheskikh riskov pri poiskakh mestorozhdenii nefti i gaza [Probabilistic forecast of geological risks when searching for oil and gas fields]. Perm': Knizhnyi mir, 2009, 224 p.
2. Liadova N.A., Iakovlev Iu.A., Raspopov A.V. Geologiia i razrabotka neftianykh mestorozhdenii Permskogo kraia [Geology and development of oil fields in the Perm Krai]. Moscow: VNIIOENG, 2010, 335 p.
3. Galkin V.I., Solov'ev S.I. Raionirovanie territorii Permskogo kraia po stepeni perspektivnosti priobreteniia neftianykh uchastkov nedr [Classification of Perm Krai areas according to prospectivity for oil fields acquisition]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Geologiia. Neftegazovoe i gornoe delo*, 2015, no. 16, pp. 14-24. DOI: 10.15593/224-9923/2015.16.2
4. Galkin V.I., Karaseva T.V., Kozlova I.A., Nosov M.A., Krivoshchekov S.N. Differentsirovannaia veroiatnostnaia otsenka generatsionnykh protsessov v otlozheniiakh domanikovogo tipa Permskogo kraia [Differentiated probabilistic assessment of the generation processes in Domanic sediments of Perm region]. *Neftianoe khoziaistvo*, 2014, no. 12, pp. 103-105.
5. Galkin V.I., Rastegaev A.V., Galkin S.V. Veroiatnostno-statisticheskaia otsenka neftegazonosnosti lokal'nykh struktur [Probabilistic and statistical assessment of oil and gas potential of local structures]. Ekaterinburg, 2011, 299 p.
6. Putilov I.S., Solov'ev S.I., Obukhov A.A., Piatunina E.V. Kompleksnyi podkhod k izucheniiu domanikovykh otlozhenii na territorii Permskogo kraia [An integrated approach to the study of Domanik deposits in the Perm region]. *Perspektivy uvelicheniia resursnoi bazy razrabatyvaemykh otlozhenii, v tom chisle iz domanikovykh otlozhenii. Sbornik dokladov po itogam mezhregional'noi nauchno-prakticheskoi konferentsii, posviashchennoi 70-letiiu NGDU "Leninogorskneft'", Karabash, 6-7 August 2015*. Al'met'evsk: PAO "Tatneft'", 2015, pp. 71-78.
7. Mikhalevich I.M. Primenenie matematicheskikh metodov pri analize geologicheskoi informatsii (s ispol'zovaniem komp'iuternykh tekhnologii) [Application of mathematical methods in the analysis of geological information (using computer technology)]. Irkutsk, 2006, 115 p.
8. Galkin S.V., Lobanov D.S. Ispol'zovanie mnogomernykh statisticheskikh modelei pri operativnom kontrole izvlekaemykh zapasov vizeiskikh zalezhei Permskogo kraia [Use of multidimensional statistical models for operational control of recoverable reserves for the Visean deposits of the Perm region]. *Izvestiia Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov*, 2022, vol. 333, no. 5, pp. 126-136. DOI: 10.18799/24131830/2022/5/3463
9. Dement'ev L.F. Matematicheskie metody i EVM v neftegazovoi geologii [Mathematical methods and computers in oil and gas geology]. Moscow: Nedra, 1987, 264 p.
10. Cosentino L. Integrated reservoir studies. Paris: Editions Technip, 2001, 400 p.
11. Diubrul' O. Ispol'zovanie geostatistiki dlia vkliucheniia v geologicheskuiu model' seismicheskikh dannykh [Using geostatistics to incorporate seismic data into a geological model]. Moscow, Evropeiskaia assotsiatsiia geouchenykh i inzhenerov (EAGE), 2002, 296 p.
12. Armstrong M. Basic Linear Geostatistics. Springer, 1998, 155 p.
13. Iuzhakov A.L. Prognoz neftegazonosnosti struktur po tektonicheskim elementam otrazhaiushchego gorizonta IIK iuzhnoi chasti Permskogo kraia [Forecast of oil and gas content of structures based on tectonic elements of reflecting horizon IIK in the southern part of the Perm Krai]. *Novye napravleniia neftegazovoi geologii i geokhimii. Razvitie geologorazvedochnykh rabot. Sbornik materialov II Mezhdunarodnoi nauchnoi konferentsii*. Perm', 2019, pp. 195-200.
14. Galkin V.I., Kozlova I.A., Melkishev O.A., Shadrina M.A. Geokhimicheskie pokazateli ROV porod kak kriterii otsenki perspektiv neftegazonosnosti [Geochemical indicators of dispersed organic matter (DOM) of rocks as criteria of hydrocarbon potential evaluation]. *Neftepromyslovoe delo*, 2013, no. 9, pp. 28-31.
15. Altunin A.E., Semukhin M.V. Raschety v usloviiakh riska i neopredelennosti v neftegazovykh tekhnologiiakh [Calculations under conditions of risk and uncertainty in oil and gas technologies]. Moscow, Tiumen': Tiumenskii gosudarstvennyi universitet, 2004, 296 p.
16. Krivoshchekov S.N., Galkin V.I., Volkova A.S. Razrabotka veroiatnostno-statisticheskoi metodiki prognoza neftegazonosnosti struktur [Development of a probabilistic-statistical methodology for predicting the oil and gas content of structures]. *Neftepromyslovoe delo*, 2010, no. 7, pp. 28-31.
17. Kaufman M.G. Statistical issues in the assessment of undiscovered oil and gas resources. MITCEEPR, 1992, 30 p.
18. Horne R.N. Modern well test analysis: A computer aided approach. 2nd ed. Palo Alto: Petroway Inc, 2006, 257 p.
19. Isaaks E.H., Srivastava R.M. An Introduction to Applied Geostatistics. Oxford University Press, 1989, 561 p.
20. Deutsch C.V. Geostatistical Reservoir modelling. Oxford University Press, 2002.
21. Montgomery D.C., Peck E.A., Introduction to linear regression analysis. New York: John Wiley & Sons, 1982, 504 p.
22. Houze O., Viturat D., Fjaere O.S. Dinamie data analysis. Paris: Kappa Engineering, 2008, 694 p.
23. Voevodkin V.L., Galkin V.I., Krivoshchekov S.N. Issledovanie vliianiia kriteriev neftegazonosnosti i izuchennosti territorii Permskogo kraia na raspredelenie mestorozhdenii uglevodorodov [Investigation of the influence of oil and gas content criteria and geological and geophysical knowledge on the distribution of hydrocarbon deposits in the Perm Region]. *Neftianoe khoziaistvo*, 2012, no. 6, pp. 30-34.
24. Putilov I.S. Nauchnoe obosnovanie veroiatnostno-statisticheskikh metodov prognoza neftegazonosnosti struktur v usloviiakh vysokoizuchennykh territorii [Scientific substantiation of probabilistic and statistical methods for predicting the oil and gas content of structures in highly studied areas]. Perm', 2016, 369 p.
25. Fokin A. Riski i neopredelennosti v geologorazvedochnom protsesse [Risks and uncertainties in the geological exploration process]. *Novator*, 2011, no. 43, pp. 8-12.
26. Galkin V.I., Zhukov Iu.A., Shishkin M.A. Primenenie veroiatnostnykh modelei dlia lokal'nogo prognoza neftegazonosnosti [Application of probabilistic models for local forecast of oil and gas content]. Ekaterinburg: Ural'skoe otdelenie Rossiiskoi akademii nauk, 1990, 108 p.
27. Ampilov Iu.P. Metody geologo-ekonomicheskogo modelirovaniia resursov i zapasov nefti i gaza s uchetom neopredelennosti i riska [Methods for geological and economic modeling of oil and gas resources and reserves taking into account uncertainty and risk]. Moscow: Geoinformmark, 2002, 201 p.
28. Galkin V.I., Kozlova I.A., Krivoshchekov S.N., Piatunina E.V., Pestova S.N. O vozmozhnosti prognozirovaniia neftegazonosnosti famenskikh otlozhenii s pomoshch'iu postroeniia veroiatnostno-statisticheskikh modelei [On the possibility of predicting the oil and gas content of Famennian deposits using the construction of probabilistic-statistical models]. *Geologiia, geofizika i razrabotka neftianykh i gazovykh mestorozhdenii*, 2007, no. 10, pp. 22-27.
29. Krivoshchekov S.N., Galkin V.I. Postroenie matritsy elementarnykh iacheek pri prognoze neftegazonosnosti veroiatnostno-statisticheskimi metodami na territorii Permskogo kraia [Construction of a matrix of elementary cells when predicting oil and gas content using probabilistic and statistical methods in the Perm Krai]. *Geologiia, geofizika i razrabotka neftianykh i gazovykh mestorozhdenii*, 2008, no. 8, pp. 20-23.
30. Putilov I.S., Galkin V.I. Razrabotka metodiki veroiatnostno-statisticheskogo prognoza neftegazonosnosti lokalizovannykh struktur (na primere iuzhnoi chasti Permskogo kraia) [Developing the technology for probabilistic and statistical forecast of oil-and-gas-bearing capacity of the South Perm Region]. *Neftianoe khoziaistvo*, 2014, no. 4, pp. 26-29.
31. Yarus J.M. Stochastic modeling and geostatistics. *AAPG*. Tulsa, Oklahoma, 1994, 231 p.
32. Davydenko A.Iu. Veroiatnostno-statisticheskie metody v geologo-geofizicheskikh prilozheniiakh [Probabilistic-statistical methods in geological and geophysical applications]. Irkutsk, 2007, 29 p.
33. GSLIB: Geostatistical Software Library and User's Guide. New York: Oxford University Press, 1998, 369 p.
34. Zhuoheng Ch., Osadetz K.G. Geological Risk Mapping and Prospect Evaluation Using Multivariate and Bayesian Statistical Methods, Western Sverdrup Basin of Canada. *AAPG Bulletin*, 2006, vol. 90, no. 6, pp. 859-872. DOI: 10.1306/01160605050
35. Pomorskii Iu.L. Metody statisticheskogo analiza eksperimental'nykh dannykh: monografiia [Methods of statistical analysis of experimental data: monograph]. Leningrad, 1960, 174 p.
36. Krivoshchekov S.N. Razrabotka regional'no-zonal'nykh kriteriev prognoza neftegazonosnosti territorii Permskogo Prikam'ia veroiatnostno-statisticheskimi metodami [Development of regional-zonal criteria for forecasting oil and gas content of the Perm Kama region using probabilistic and statistical methods]. *Neftianoe khoziaistvo*, 2011, no. 10, pp. 10-14.
37. Davis J.C. Statistics and Data Analysis in Geology. 3Rd Edition. John Wiley & Sons, 2002, 656 p.
38. Meisner J., Demirmen F. The creaming method: a bayesian procedure to forecast future oil and gas discoveries in mature exploration provinces. *Journal of the Royal Statistical Society. Series A*, 1981, vol. 144, no. 1, pp. 1-31. DOI: 10.2307/2982158
39. Johnson N.L., Leone F.C. Statistics and experimental design. New York - London - Sydney - Toronto, 1977, 606 p.
40. Putilov I.S., Galkin V.I. Primenenie veroiatnostnogo statisticheskogo analiza dlia izucheniia fatsial'noi zonal'nosti turne-famenskogo karbonatnogo kompleksa Sibirskogo mestorozhdeniia [Application of probabilistic statistical analysis to study the facies zoning of the Tournai-Famennian carbonate complex of the Siberian field]. *Neftianoe khoziaistvo*, 2007, no. 9, pp. 112-114.

41. Krivoshchekov S.N., Kochnev A.A., Sannikov I.V. Perspektivy neftegazonosnosti otlozhenii domanikovogo tipa na territorii Permskogo kraia [Oil and gas prospects of domanic sediments in Perm Krai]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Geologiia. Neftegazovoe i gornoe delo*, 2013, no. 9, pp. 18-26. DOI: 10.15593/2224-9923/2013.9.2
42. Putilov I.S. Razrabotka tekhnologii kompleksnogo izucheniia geologicheskogo stroeniia i razmeshcheniia mestorozhdenii nefti i gaza [Development of technologies for comprehensive study of the geological structure and location of oil and gas fields]. Perm': Permskii natsional'nyi issledovatel'skii politekhnicheskii universitet, 2014, 285 p.
43. Iuzhakov A.L. Klassifikatsiia strukturnykh lokal'nykh ostatkov otrazhaiushchego gorizonta IIK na primere iuga Permskogo kraia [Classification of structural local remains of the reflecting horizon IIK using the example of the south of the Perm Krai]. *Problemy razrabotki mestorozhdenii uglevodorodnykh i rudnykh poleznykh iskopaemykh. Materialy XI Vserossiiskoi nauchno- tekhnicheskoi konferentsii, Perm', 7-9 November 2018*. Perm', 2018, 85 p.
44. Meng L., Zhen L., Minzhu L., Huilai Z. Prediction of residual oil satiration by using the ratio of amplitude of time-lapse seismic data. *Geophysics*, 2017, vol. 82, no. 1, pp. 1-12. DOI: 10.1190/geo2015-0453.1
45. Kovalevskiy E. Geological Modelling on the Base of Geostatistics: Course Note. Student Lecture Tour. RUSSIA & CIS, 2011-2012.
46. Putilov I.S. Trekhmernoe geologicheskoe modelirovanie pri razrabotke neftianykh i gazovykh mestorozhdenii [3D geological modeling for oil and gas field development]. Perm': Permskii natsional'nyi issledovatel'skii politekhnicheskii universitet, 2011, 72 p.

Библиографический список

1. Галкин С.В. Вероятностный прогноз геологических рисков при поисках месторождений нефти и газа. – Пермь: Книжный мир, 2009. – 224 с.
2. Лядова Н.А., Яковлев Ю.А., Распопов А.В. Геология и разработка нефтяных месторождений Пермского края. – М.: ВНИИОЭНГ, 2010. – 335 с.
3. Галкин В.И., Соловьев С.И. Районирование территории Пермского края по степени перспективности приобретения нефтяных участков недр // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2015. – № 16. – С. 14–24. DOI: 10.15593/224-9923/2015.16.2
4. Дифференцированная вероятностная оценка генерационных процессов в отложениях доманикового типа Пермского края / В.И. Галкин, Т.В. Карасева, И.А. Козлова, М.А. Носов, С.Н. Кривощеков // Нефтяное хозяйство. – 2014. – № 12. – С. 103–105.
5. Галкин В.И., Растегаев А.В., Галкин С.В. Вероятностно-статистическая оценка нефтегазоносности локальных структур. – Екатеринбург, 2011. – 299 с.
6. Комплексный подход к изучению доманиковых отложений на территории Пермского края / И.С. Путилов, С.И. Соловьев, А.А. Обухов, Е.В. Пятунина // Перспективы увеличения ресурсной базы разрабатываемых отложений, в том числе из доманиковых отложений: сборник докладов по итогам межрегион. науч.-практ. конф., посвященной 70-летию НГДУ «Лениногорскнефть», Карабаш, 6–7 августа 2015 г. / ПАО «Татнефть». – Альметьевск, 2015. – С. 71–78.
7. Михалевич И.М. Применение математических методов при анализе геологической информации (с использованием компьютерных технологий). – Иркутск, 2006. – 115 с.
8. Галкин С.В., Лобанов Д.С. Использование многомерных статистических моделей при оперативном контроле извлекаемых запасов визейских залежей Пермского края // Известия Томского политехнического университета. Инжиниринг георесурсов. – 2022. – Т. 333, № 5. – С. 126–136. DOI: 10.18799/24131830/2022/5/3463
9. Дементьев Л.Ф. Математические методы и ЭВМ в нефтегазовой геологии. – М.: Недра, 1987. – 264 с.
10. Cosentino L. Integrated reservoir studies. – Paris: Editions Technip, 2001. – 400 p.
11. Дюбрюль О. Использование геостатистики для включения в геологическую модель сейсмических данных / Евр. ассоциация геоученых и инженеров (EAGE). – М., 2002. – 296 с.
12. Armstrong M. Basic Linear Geostatistics. – Springer, 1998. – 155 p.
13. Южаков А.Л. Прогноз нефтегазоносности структур по тектоническим элементам отражающего горизонта IIК южной части Пермского края // Новые направления нефтегазовой геологии и геохимии. Развитие геологоразведочных работ: сборник материалов II Междунар. науч. конф. – Пермь, 2019. – С. 195–200.
14. Геохимические показатели РОВ пород как критерии оценки перспектив нефтегазоносности / В.И. Галкин, И.А. Козлова, О.А. Мелкишев, М.А. Шадрина // Нефтепромысловое дело. – 2013. – № 9. – С. 28–31.
15. Алтунин А.Е., Семухин М.В. Расчеты в условиях риска и неопределенности в нефтегазовых технологиях. – М.; Тюмень: Изд-во Тюмен. гос. ун-та, 2004. – 296 с.
16. Кривощеков С.Н., Галкин В.И., Волкова А.С. Разработка вероятностно-статистической методики прогноза нефтегазоносности структур // Нефтепромысловое дело. – 2010. – № 7. – С. 28–31.
17. Kaufman M.G. Statistical issues in the assessment of undiscovered oil and gas resources. – MITCEEPR, 1992. – 30 p.
18. Horne R.N. Modern well test analysis: A computer aided approach. – 2nd ed. – Palo Alto: Petroway Inc, 2006. – 257 p.
19. Isaaks E.H., Srivastava R.M. An Introduction to Applied Geostatistics. – Oxford University Press, 1989. – 561 p.
20. Deutsch C.V. Geostatistical Reservoir modelling. – Oxford University Press, 2002.
21. Montgomery D.C., Peck E.A., Introduction to linear regression analysis. – New York: John Wiley & Sons, 1982. – 504 p.
22. Houze O., Viturat D., Fjaere O.S. Dinamie data analysis. – Paris: Kappa Engineering, 2008. – 694 p.
23. Воеводкин В.Л., Галкин В.И., Кривощеков С.Н. Исследование влияния критериев нефтегазоносности и изученности территории Пермского края на распределение месторождений углеводородов // Нефтяное хозяйство. – 2012. – № 6. – С. 30–34.
24. Путилов И.С. Научное обоснование вероятностно-статистических методов прогноза нефтегазоносности структур в условиях высокоизученных территорий. – Пермь, 2016. – 369 с.
25. Фокин А. Риски и неопределенности в геологоразведочном процессе // Новатор. – 2011. – № 43. – С. 8–12.
26. Галкин В.И., Жуков Ю.А., Шишкин М.А. Применение вероятностных моделей для локального прогноза нефтегазоносности. – Екатеринбург: Изд-во Уро РАН, 1990. – 108 с.
27. Ампилов Ю.П. Методы геолого-экономического моделирования ресурсов и запасов нефти и газа с учетом неопределенности и риска. – М.: Геоинформмарк, 2002. – 201 с.
28. О возможности прогнозирования нефтегазоносности фаменских отложений с помощью построения вероятностно-статистических моделей / В.И. Галкин, И.А. Козлова, С.Н. Кривощеков, Е.В. Пятунина, С.Н. Пестова // Геология, геофизика и разработка нефтяных и газовых месторождений. – 2007. – № 10. – С. 22–27.
29. Кривощеков С.Н., Галкин В.И. Построение матрицы элементарных ячеек при прогнозе нефтегазоносности вероятностно-статистическими методами на территории Пермского края // Геология, геофизика и разработка нефтяных и газовых месторождений. – 2008. – № 8. – С. 20–23.
30. Путилов И.С., Галкин В.И. Разработка методики вероятностно-статистического прогноза нефтегазоносности локализованных структур (на примере южной части Пермского края) // Нефтяное хозяйство. – 2014. – № 4. – С. 26–29.
31. Yarus J.M. Stochastic modeling and geostatistics // AAPG. – Tulsa, Oklahoma, 1994. – 231 p.
32. Давыденко А.Ю. Вероятностно-статистические методы в геолого-геофизических приложениях. – Иркутск, 2007. – 29 с.
33. GSLIB: Geostatistical Software Library and User's Guide. – New York: Oxford University Press, 1998. – 369 p.
34. Zhuoheng Ch., Osadetz K.G. Geological Risk Mapping and Prospect Evaluation Using Multivariate and Bayesian Statistical Methods, Western Sverdrup Basin of Canada // AAPG Bulletin. – 2006. – Vol. 90, № 6. – P. 859–872. DOI: 10.1306/01160605050
35. Поморский Ю.Л. Методы статистического анализа экспериментальных данных: монография. – Л., 1960. – 174 с.
36. Кривощеков С.Н. Разработка регионально-зональных критериев прогноза нефтегазоносности территории Пермского Прикамья вероятностно-статистическими методами // Нефтяное хозяйство. – 2011. – № 10. – С. 10–14.
37. Davis J.C. Statistics and Data Analysis in Geology. – 3Rd Edition. – John Wiley & Sons, 2002. – 656 p.
38. Meisner J., Demirmen F. The creaming method: a bayesian procedure to forecast future oil and gas discoveries in mature exploration provinces // Journal of the Royal Statistical Society. Series A. – 1981. – Vol. 144, № 1. – P. 1–31. DOI: 10.2307/2982158
39. Johnson N.L., Leone F.C. Statistics and experimental design. – New York – London – Sydney – Toronto, 1977. – 606 p.
40. Путилов И.С., Галкин В.И. Применение вероятностного статистического анализа для изучения фациальной зональности турне-фаменского карбонатного комплекса Сибирского месторождения // Нефтяное хозяйство. – 2007. – № 9. – С. 112–114.
41. Кривощеков С.Н., Кочнев А.А., Санников И.В. Перспективы нефтегазоносности отложений доманикового типа на территории Пермского края // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2013. – № 9. – С. 18–26. DOI: 10.15593/2224-9923/2013.9.2
42. Путилов И.С. Разработка технологий комплексного изучения геологического строения и размещения месторождений нефти и газа. – Пермь: Изд-во Перм. нац. исслед. политехн. ун-та, 2014. – 285 с.
43. Южаков А.Л. Классификация структурных локальных остатков отражающего горизонта IIК на примере юга Пермского края // Проблемы разработки месторождений углеводородных и рудных полезных ископаемых: материалы XI Всерос. науч.- техн. конф., г. Пермь, 7–9 ноября 2018 г. – Пермь, 2018. – С. 85.
44. Prediction of residual oil satiration by using the ratio of amplitude of time-lapse seismic data / L. Meng, L. Zhen, L. Minzhu, Z. Huilai // Geophysics. – 2017. – Vol. 82, № 1. – P. 1–12. DOI: 10.1190/geo2015-0453.1
45. Kovalevskiy E. Geological Modelling on the Base of Geostatistics: Course Note. – Student Lecture Tour. – RUSSIA & CIS, 2011–2012.
46. Путилов И.С. Трехмерное геологическое моделирование при разработке нефтяных и газовых месторождений. – Пермь: Изд-во Перм. нац. исслед. политехн. ун-та, 2011. – 72 с.

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