DEVELOPING A STATISTICAL MODEL OF OIL AND GAS POTENTIAL PREDICTION
BY GAS SHOWINGS IN THE VERKHNEKAMSKOYE DEPOSIT STRATA
OF POTASSIUM AND MAGNESIUM SALTS

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RAZREBOTA STATISTICHESKOYI MODELYI PROGNOZA
NEFTEGAZOOSNOSNOTI PO GAZOVYDLELENIYAM V TOLSHHE
VERKHNEKAMSKOGO MESTOROZHDENIIA KALIINO-MAGNIEVYKH SOLEI

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Perm Krai.

Abstract:

The Verkhnekamskoye deposit of potassium and magnesium salts is located in Solikamsk depression within Pre-Urals foreland basin. There is a salt deposit in the near-surface section, with a number of oil and gas deposits below it. The gas-oil ratio is known to be central to the process of gas showings during drilling of geological exploration wells and initiation of gas production. Following this dependency, operations for the purpose of salt extraction.

The obtained individual probabilities served the basis for obtaining a discriminant function (Zm) to predict the gas potential in the salt massive. The obtained values of Zm discriminant function were used to build a regression model of oil and gas potential prediction P(Y). Following this dependency, P(Y) values were calculated for all 856 studied salt exploration wells.

The average value (± standard deviation) of the probability for the class within the outline of the oil and gas zone was 0.51 ± 0.0086 unit fractions. For the class outside the oil and gas zone, the average value was 0.490 ± 0.0070 unit fractions. The obtained models enable constructing gas-show prediction schemes and an oil and gas potential prediction scheme for the Verkhnekamskoye salt deposit.

Key words:
oil and gas potential prediction, gas content of salts, gas-dynamic effects, probabilistic and statistical models, probability, Verkhnekamskoye deposit of potassium and magnesium salts, Perm Krai.

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Introduction

The Verkhnekamskoye deposit of potassium and magnesium salts (VKDMS) is located in Solikamsk depression within Pre-Urals foreland basin. There is a salt deposit in the near-surface section, with a number of oil and gas deposits below it. This area is of great interest when studying oil and gas content distribution in the section [1–10].

The gas-oil ratio is known to be central to the process of gas showings in drilling geological exploration wells and to gas-dynamic effects in the underground operations. For this purpose, all evidence on gas showings recorded during the salt exploration wells drilling at the Verkhnekamskoye potash deposit was collected, as reflected in archival data and reports on prospect evaluation surveys. The findings were summarized and used to build a probabilistic and statistical model of oil and gas potential prediction.

The possibilities of geological and mathematical model-building to address various geological problems are given in [11–14]. We applied the methods of mathematical statistics and probability theory to one-dimensional and multidimensional linear statistical model-building. These methods are in details described in works of both Russian and foreign authors [15–30].

Development of Gas Potential Prediction Models for the VKDMS Strata

Initially, for the development of gas showings prediction models, the average values for the areas [31–45] with the gas showings (Class 1) were compared with those for the areas with no gas showings observed (Class 2). For this we used a training sample of 374 wells (Fig. 1).

The analysis was conducted using various statistical criteria by the following characteristics: \(M_{\text{salt}}\) is the thickness of the overlying rock salt, \(M_{\text{potash}}\) is the potash layer thickness (from the 1st potash layer to the bottom of salts), \(N_f\) is the quantity of formations in the section, \(M_s\) is the thickness of salt stratum, \(M_K\) is the thickness of formation K, \(M_I\) is the thickness of formation I, \(M_Z\) is the thickness of formation Z, \(M_{IZ}\) is the thickness of formation Zh, \(M_E\) is the thickness of formation E, \(M_D\) is the thickness of formation D, \(M_{K1}\) is the thickness of formation V, \(M_{B}\) is the thickness of formation B, \(M_{AB}\) is the thickness of formation AB, \(M_{A}\) is the thickness of formation A, \(M_{K1}\) is the thickness of formation K1, \(M_{K2}\) is the thickness of formation K2, \(M_{K3}\) is the thickness of formation K3.

We compared the distributions using the Student’s t-test [11] and Pearson’s \(\chi^2\) test.

The studies consisted in comparing mean values of the indicators and building probability models of pertaining to the class of territories with gas showings (Table 1).
Comparison of Mean Values and Individual Probabilistic Models by Formation Thickness

| Indicator | Statistical characteristics of indicators * | Criterion | Probability equation of pertaining to territory class with gas-show | Model application field | Probability variation range |
|-----------|---------------------------------------------|-----------|---------------------------------------------------------------|-------------------------|---------------------------|
| M^min, m  | 22.7 ± 2.1 \( \pm 0.506 \pm 0.063 \) | 20.3 ± 0.5 \( 0.488 \pm 0.059 \) | 2.817 858.5 ± 0.014 | \( P^M_{\min} = 0.306 + 0.0090 \ M^\min \) | 0.5–76.5 m 0.31–0.99 |
| M^predn, m | 78.8 ± 22.6 \( 0.531 \pm 0.120 \) | 64.1 ± 25.6 \( 0.453 \pm 0.135 \) | 5.898 34.25 ± 0.010 |
| M^z, m    | 11.7 ± 1.8 \( 0.523 \pm 0.076 \) | 10.7 ± 25.6 \( 0.480 \pm 0.135 \) | 4.230 36.18 ± 0.010 |
| M^in, m   | \( 100.0 \pm 23.0 \) \( 0.540 \pm 0.142 \) | 82.0 ± 27.6 \( 0.440 \pm 0.151 \) | 6.845 45.83 ± 0.010 |
| M^x, m    | 0.93 ± 0.41 \( 0.501 \pm 0.024 \) | 0.89 ± 0.40 \( 0.498 \pm 0.151 \) | 0.967 1.931 ± 0.039 |
| M^z, m    | 1.16 ± 0.63 \( 0.502 \pm 0.032 \) | 1.08 ± 0.60 \( 0.497 \pm 0.031 \) | 1.252 1.895 ± 0.021 |
| M^v, m    | 0.58 ± 0.36 \( 0.501 \pm 0.013 \) | 0.62 ± 0.54 \( 0.499 \pm 0.018 \) | 0.629 1.404 ± 0.034 |
| M^x, m    | 0.80 ± 0.47 \( 0.500 \pm 0.007 \) | 0.79 ± 0.35 \( 0.499 \pm 0.005 \) | 0.243 1.125 ± 0.034 |
| M^z, m    | 8.82 ± 5.07 \( 0.511 \pm 0.069 \) | 6.68 ± 4.28 \( 0.482 \pm 0.005 \) | 4.401 23.41 ± 0.000 |
| M^v, m    | 9.86 ± 5.85 \( 0.511 \pm 0.069 \) | 7.63 ± 5.90 \( 0.482 \pm 0.005 \) | 3.657 16.14 ± 0.000 |
| M^v, m    | 7.70 ± 5.24 \( 0.505 \pm 0.072 \) | 6.02 ± 4.26 \( 0.482 \pm 0.005 \) | 3.401 14.17 ± 0.000 |
| M^v, m    | 6.69 ± 3.26 \( 0.502 \pm 0.012 \) | 5.28 ± 3.62 \( 0.497 \pm 0.014 \) | 3.947 16.67 ± 0.000 |
| M^v, m    | 2.01 ± 0.89 \( 0.501 \pm 0.011 \) | 1.89 ± 1.23 \( 0.499 \pm 0.015 \) | 0.996 2.021 ± 0.000 |
| M^v, m    | 3.64 ± 1.15 \( 0.503 \pm 0.026 \) | 3.36 ± 1.73 \( 0.497 \pm 0.040 \) | 1.798 4.01 ± 0.000 |
| M^v, m    | 1.65 ± 0.61 \( 0.503 \pm 0.012 \) | 1.49 ± 0.69 \( 0.499 \pm 0.014 \) | 2.374 5.00 ± 0.000 |
| M^v, m    | 1.14 ± 0.42 \( 0.503 \pm 0.025 \) | 1.04 ± 0.40 \( 0.496 \pm 0.024 \) | 2.717 6.21 ± 0.000 |
| M^v, m    | 4.64 ± 1.61 \( 0.501 \pm 0.018 \) | 4.51 ± 1.89 \( 0.499 \pm 0.021 \) | 0.776 1.317 ± 0.000 |
| M^v, m    | 4.70 ± 1.92 \( 0.505 \pm 0.050 \) | 4.27 ± 2.07 \( 0.494 \pm 0.054 \) | 2.086 4.443 ± 0.000 |

Note: * in numerator: mean value ± standard deviation of the indicator; in denominator: mean value ± standard deviation of probabilities for this indicator.

These data indicate that the mean values differ statistically for the following indicators: \( M^\min, M^\predn, N^S, M^\z, M^\z, M^\v, M^\v, M^\v, M^\v \). We built a linear probabilistic models (Table 1) in order to determine the effect of each of the thickness indicators that in different ways control the direction and strength of the gas showing processes. These models made it possible to determine the probability of pertaining to the class of territories where the gas showings occurred, by each indicator.

Building the linear models [12] required initial study of their distributions. For this purpose, the Sturges’ formula was used to determine the optimum values of variability intervals for each indicator:

\[
\Delta X = \frac{X_{max} - X_{min}}{1 + 3.32 \lg N},
\]

where \( X_{max} \) were the maximum value of the indicator; \( X_{min} \) were the minimum value of the indicator; \( N \) was the data sampling size.

The frequencies were determined in each interval, as follows:

\[
P(X) = \frac{N_k}{N_f},
\]

where \( P(X) \) were frequency in the k-th interval for the class; \( N_k \) was the number of cases of the \( X \) indicator content in the k-th interval of the class; \( N_f \) was the sample size for classes 1 and 2 in the k-th interval.

Table 1
An example of the distribution by indicator $M_s$ (thickness of salts) is given in Table 2.

When comparing distributive densities of the indicators shown in Table 2, the Pearson's $\chi^2$ criterion was applied to the classes under study. The criterion values are given in Table 1. These data indicate that, by the $\chi^2$ criterion, 10 out of 18 indicators differ statistically at $p < 0.05$.

The technology of linear probabilistic modelling consists in the following.

The probability of pertaining to the territories with gas showings is determined in each interval. The interval probabilities of pertaining to Class 1 are then compared with the mean interval values for the indicators. The obtained values are used to calculate the matching correlation coefficient $r$ and to build a regression equation. The models built are then adjusted on the assumption that the mean value for the territories with gas showings should be greater than 0.5, and for the territories without gas showings – less than 0.5. Table 1 contains the regression equations built by this scheme. They are presented by thickness properties and conditions of their application.

Figure 2 provides an example of comparing two individual models by indicators $M_{fZb}$ and $M_{fK1}$.

Model $P(M_{fK1})$ has a greater value of the angular term in the equation compared to $P(M_{fZb})$, which leads to more differentiated estimates of the gas showing probability on the VKMKS territory.

The analysis of the individual models and the values of criteria $t$ and $\chi^2$ shows that the following indicators are the most informative: $M_{ors}$, $M_{potash}$, $N_f$, $M_s$, $M_{fB}$, $M_{fG}$, $M_{fV}$, $M_{fA}$, and $M_{fK1}$.

We will apply a stepwise linear discriminant analysis for the complex estimation of probabilities relationship calculated using the linear models for the gas content.

For model development, we used the data from the model sampling that had been utilised to build the linear models (Class 1: 187 values, Class 2: 187 values).

As a result of implementation of this method, the following linear discriminant function was obtained for the formation thicknesses:

$$Z_m = -17.9265 + 2.6620P(M_s) - 24.1317P(M_m) + 13.8526P(M_{fB}) + 12.6002P(M_{fK1}) + 6.1630P(M_{fE}) + 2.7958P(N_f) + 3.6734P(M_{fK3}) + 14.8381P(M_{fV}) + 6.7251P(M_{fK}) - 9.3998P(M_{fK2})$$

at $R = 0.401$, $\chi^2 = 63.9412$, $p < 10^{-5}$.
The order of indicators inclusion in the function was formed in the sequence given in the equation. These functions were used to calculate $Z_m$ values and $P(Z_m)$ probability. The ratio between $Z_m$ and $P(Z_m)$ is shown in Figure 3.

**Developing the Oil and Gas Potential Prediction Models**

Based on the received $Z_m$ values, the mean (Table 3) values for the wells located within oil and gas bearing outlines (Class 1, $n = 86$) were compared with those for the territories with no determined oil and gas content (class 2, $n = 80$). The comparison was carried out using the $t$ and $\chi^2$ criteria based on a training sample (see Fig. 4) of 166 wells.

The analysis of the $Z_m$ distributions and the probabilistic modelling of pertaining to the class of oil and gas bearing territories were conducted in the same way as with gas showings in the VKDMS strata.

These data indicate that the mean values of $Z_m$ multiple criterion statistically differ from the achieved significance level of $\rho = 0.066$ by the Student's $t$-test. To calculate the probability of pertaining to the class of oil and gas bearing areas, we shall build a linear probabilistic model that enables determining the probability of pertaining to the class of areas with oil and gas content in the section.

To build an oil and gas potential prediction model by $Z_m$ values, we analysed the $Z_m$ distribution by intervals of variability (Table 4) for the areas within the oil and gas bearing outline (Class 1) and the ones outside the outline (Class 2).

The distributions of $Z_m$ criterion by intervals of variability are given in Table 4.

| Table 4 Frequency Distribution of $Z_m$ Values |
|-----------------------------------------------|
| **Class** | $Z_m$ variability intervals | **Within oil and gas bearing outline** | **Outside oil and gas bearing outline** |
|-----------|-----------------------------|----------------------------------------|----------------------------------------|
|           | (-4.5; -3.5] | (-3.5; -2.5] | (-2.5; -1.5] | (-1.5; -0.5] | (-0.5; 0.5] | (0.5; 1.5] | (1.5; 2.5] |
| Class 1   |        |        |        |        |        |        |        |
| Class 2   |        |        |        |        |        |        |        |

| Table 3 Comparison of Mean Values and Probabilistic Models by $Z_m$ Criterion |
|------------------------------------------------------------------------------|
| **Indicator** | **Statistical characteristics of indicators (mean value ± standard deviation)** | **Statistical characteristics of indicators (mean value ± standard deviation)** | **$t$** | **$\chi^2$** |
|----------------|------------------------------------------------------------------|------------------------------------------------------------------|---|---|
| $Z_m$          | $-0.763 \pm 1.085$ | $-0.449 \pm 1.113$ | 1.841 | 3.344 |

Fig. 4. Scheme of $P(Z_m)$ Variation in the VKDMS Territory
According to the data in Table 4, the frequency for Class 1 in the interval (−0.5; 0.5) is 0.337 unit fractions, and 0.300 unit fractions for Class 2. When comparing the $Z_m$ distribution densities as shown in Table 4, the Pearson's $\chi^2$ criterion was applied to the classes under study.

The values of $\chi^2$ criterion are shown in Table 3. These data indicate that the $Z_m$ distributions statistically differ by $\chi^2$ criterion at $p = 0.019$.

In order to build a linear probabilistic model of oil and gas potential prediction based on the gas showings data for the VKDMS strata, the probabilities of pertaining to oil and gas bearing territories are determined in each interval of variability. The interval probabilities of pertaining to Class 1 are then compared with the mean interval values of $Z_m$ complex criterion. These values are used to calculate the matching correlation coefficient $r$, and to build a regression equation. The obtained models are then adjusted on the assumption that the mean value of $P_p (Z_m)$ for the oil and gas bearing territories should be greater than 0.5, and for the territories outside the oil and gas content outline – less than 0.5.

The following model of oil and gas potential probability prediction using $Z_m$ data was obtained:

$$P_p(Z_m) = 0.462-0.0635 Z_m, r = -0.67.$$  

The $Z_m$ model’s application range varies from -3.525 to 2.205. With the increase of $Z_m$ values from negative to positive, $P_p (Z_m)$ decreases from 0.682 to 0.321 unit fractions. Using this dependency, $P_p (Z_m)$ values were calculated for all 856 studied wells drilled for exploration and prospecting salt extraction operations.

**Conclusion**

In the result, the obtained mean values of the developed criterion $P_p (Z_m)$ indicate that it can be used for a zonal estimate of oil and gas content in the territory under study. The mean value of the oil and gas content probability $P_p (Z_m)$ for the areas within the oil and gas bearing outline was $0.510 \pm 0.068$ unit fractions; and $0.490 \pm 0.070$ unit fractions for the ones outside the oil and gas bearing outline.

The calculated $P_p (Z_m)$ values were used to build a scheme of oil and gas content probability for the research area (Fig. 4).

In the scheme, the probabilities $P_p (Z_m) > 0.5$ characterise the peripheral parts of the VKDMS, the $P_p (Z_m)$ values $< 0.5$ are in the central part of the VKDMS. The developed scheme can be used in planning geological exploration operations for oil production in the VKDMS territory.

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