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IDENTIFICATION ANALYSIS OF ULTRAMAFIC-MAFIC INTRUSIONS OF THE MAMONSKY COMPLEX VORONEZH CRYSTALLINE MASSIF

O.M. Muravina, M.N. Chernyshova, V.I. Zhavoronkin

Voronezh State University, Voronezh, Russia, 394006; e-mail: muravina@geol.vsu.ru

The paper discusses the methods and results of identification analysis of the petrophysical parameters of ultramafic-mafic rocks of the mamonsky intrusive complex of the Khopersky megablock of the Voronezh crystalline massif. To form identification models, one of the wells within the Nizhnemamonskoye deposit was chosen as the reference one. For different types of rocks characteristic correlation equations of the relationship of density with other petrophysical parameters were obtained. The obtained identification equations of the reference well were applied to similar rocks of other (ordinary) wells located within the Khopersky megablock. The modeling showed the possibility of applying the method of group accounting of arguments for solving the most important task — the differentiation of even-aged intrusions into ore and barren.

Keywords: group accounting method of arguments, petrophysics, Voronezh crystalline massif.

INTRODUCTION

Petrophysical information is a necessary link in the logical scheme of geological and geophysical interpretation, on the basis of which a transition is made from the physical to the geological model of the medium. A characteristic feature of the actual petrophysical data is their uneven localization in space. Large volumes of petrophysical data need to be generalized, for this purpose, in addition to traditional statistical processing, robust analysis methods are actively used. In the case of incomplete information, stochastic methods for estimating parameters using the Monte Carlo method and correlation methods for data analysis are effective (Glaznev et al., 2016). Presentation of petrophysical data in the format of three-dimensional complex petrophysical models based on geoinformation technologies can effectively eliminate the problems associated with the uneven distribution of petrophysical information. Petrophysical models actually formalize a priori data, and their use as starting environment models in the process of integrated interpretation of geophysical fields provides the geological content of the results. In the formation of petrophysical models, it is necessary to solve probabilistic-statistical problems, such as processing, analysis and generalization

of data on the physical properties of rocks. New methods of inductive modeling based on the method of group analysis of arguments allow efficient robust assessment and identification analysis of a large amount of petrophysical information (Glaznev et al., 2016; Muravina et al., 2019b). Together with traditional statistical processing, these procedures make it possible to exclude outliers in the data, to identify the belonging of a sample to one or another petrographic type of rocks or to structural complex. In this paper, we consider the methodology and results of identification modeling by the method of group accounting of arguments in the process of analyzing the petrophysical characteristics of ultramafic-mafic rocks of various intrusions of the mamonsky complex of the Khopersky megablock of the Voronezh crystalline massif (VKM) (Fig. 1).

GENERAL PROVISIONS

The method of group accounting of arguments is a data analysis method based on inductive modeling (Ivakhnenko, 1982). In English-language publications, the method is called the Group Method of Data Handlin (GMDH) (Aksenova et al, 2001; Farrow, 1984; Fernández & Lozano, 2010, (Kondo et al., 1999; Upadhyaya, Lu, 2004). Method allows you to analyze multicomponent systems and is able to identify hidden

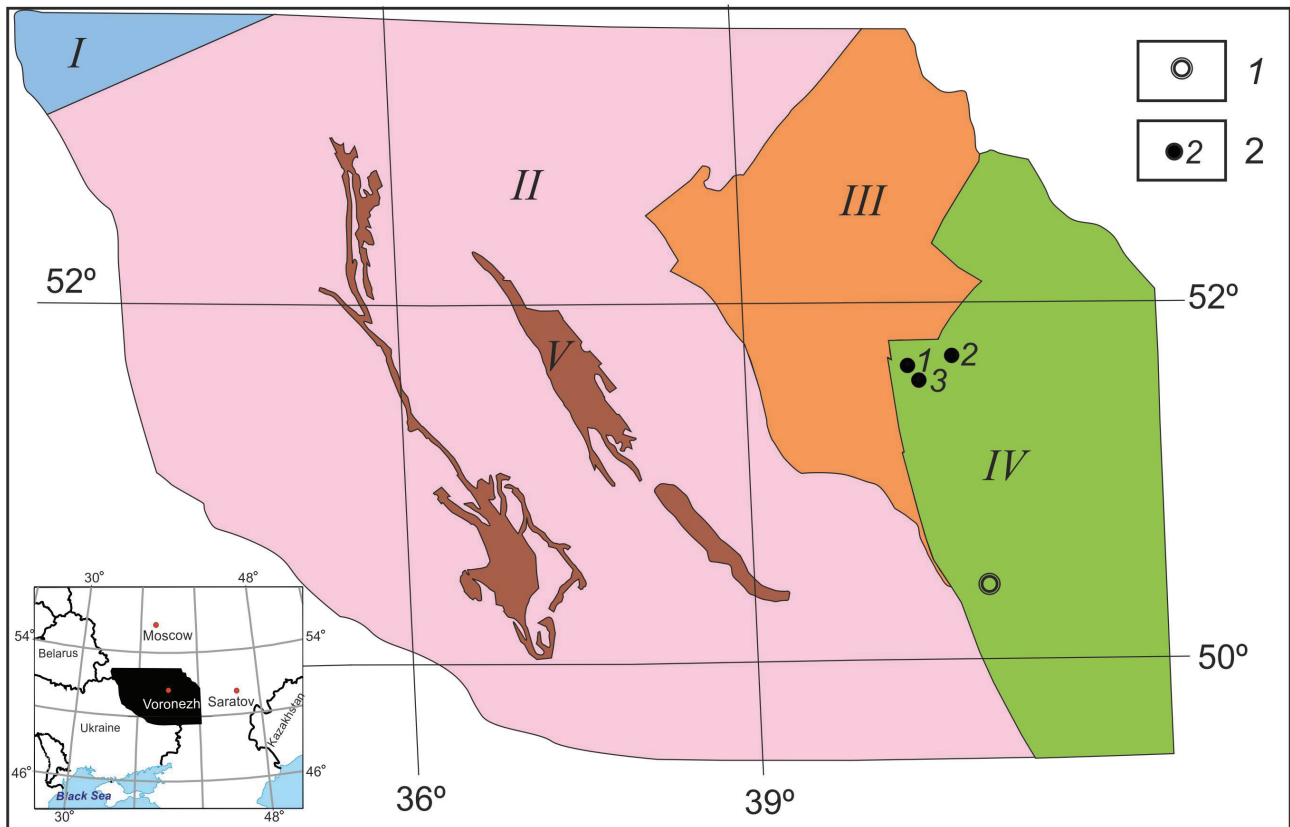


Fig. 1. The scheme of structural-tectonic zoning of the Voronezh Crystalline Massif: *I* — Bryansk megablock; *II* — megablock KMA; *III* — Losevskaya suture zone; *IV* — Hopersky megablock; *V* — zones of development of ferruginous quartzite KMA; 1 — Nizhnemamonsky deposit; 2 — location of the Mamonsky type intrusions; 3 — Sukhobiryzovsky typhon.

relationships, including non-linear, between elements. GMDH algorithms allow you to create and test many options for mathematical models and determine the model equation of optimal complexity. Generation of models is carried out combinatorially on the basis of the support function. The best model is selected by the minimum values of the external criteria. External criteria are calculated from data that are not involved in the procedure for determining the structure and parameters of the model. The features of the GMDH algorithm allow us to consider it as an alternative to multi-level neural networks. Most often, as a support function the Kolmogorov-Gabor polynomial is used. The multi-level structure of the algorithm allows you to consistently increase the degree of the polynomial and the number of variable-arguments when moving to the next level (row). So when using the Kolmogorov-Gabor polynomial of the first degree, in the models of the first row, the dependent variable y is expressed as follows:

$$Y = a_0 + a_1 X_1 + a_2 X_2 + a_3 X_1 X_2, \quad (1)$$

where a_0, a_1, a_2, a_3 — are the numerical coefficients; X_1, X_2 — argument variables.

Models of the second row have the type:

$$Y = b_0 + b_1 Z_1 + b_2 Z_2 + b_3 Z_1 Z_2, \quad (2)$$

where b_0, b_1, b_2, b_3 — are the numerical coefficients; Z_1, Z_2 — the best models of the first row, who moved to the second row.

Thus, by passing to each next row, the complexity of the models increases. For example, the model equation of the third row can have a fourth degree and contain up to eight variable arguments. Calculation of numerical coefficients is carried out on a training sequence of observations. The use of polynomials as a support function gave another name to the method — polynomial neural networks (Yurachkovsky, 1981).

In recent decades, in connection with the development of information technology, the method is actively developed and applied in various scientific and applied fields, both in Russia and abroad (Antipov, 2017; Boyarinov, 2006; Kalinina, 2016; Fernández, Lozano, 2010; Hiassat, et al., 2004; Upadhyaya, Lu, 2004). The method has proven effective in solving forecasting problems in the economy and social sphere (Boyarinov, 2006; Startsev, 2017), in ecology (Kalinina, 2016), in mining (Antipov, 2017; Shurygin et al., 2014), in oil industry (Skobelev et al., 2015) and others.

Since 2009, the Department of Geophysics of Voronezh State University the research aimed at studying the possibility of the method when working with geological and geophysical information is underway (Zhavoronkin, Faustova, 2018; Muravina, 2012; Muravina et al., 2019a). An important part of these studies is the analysis of petrophysical data (Muravina, 2009, 2013; Muravina, Glaznev, 2014; Muravina et al., 2013).

RESEARCH CHARACTERISTIC

The nickel-platinum-bearing dunite-peridotite-gabbro formation of the mamonsky complex is developed within the Khopersky megablock of the VKM (Fig. 1). It is represented by various types of intrusive bodies formed under conditions of unequal levels of magma generation. These intrusive bodies differ in structural position, levels of erosion, completeness of differentiation, saturation with dike formations, scale and degree of non-ferrous and noble metals productivity. At present, four types of intrusions are distinguished (Chernyshov, 1986; Chernyshova, 1999): 1) early ultramafic high and moderate magnesian differentiated, non-feldspar (mamonsky type); 2) ultramafic-mafic moderate magnesian chamber-differentiated (shiryaevsky type); 3) ultramafic-mafic phasic (elan-vyazovsky type); 4) slightly differentiated and undifferentiated gabbroid intrusions (kamensky type).

The object of our study is ultramafic-mafic rocks of intrusions of the first type (mamonsky type). Among them, in turn, the following varieties are distinguished by a set of features (composition and completeness of differentiation of intrusions, degree of their productivity):

- clearly differentiated moderately magnesian, with a complete association of the syngenetic series of ultramafic rocks and accompanied by sulfide platinum-copper-nickel deposits and ore deposits (for example, Nizhnemamonskoye deposit, Astakhovskoye ore occurrence);

- differentiated moderately magnesian with an incomplete association of the syngenetic series of ultramafites (peridotites-olivine pyroxenites). They are associated with numerous manifestations of sulfide platinum-copper-nickel ores of various sizes on a resource scale (for example, the Shishovskoye ore occurrence);

- undifferentiated (mainly hornblende varieties of peridotites and olivine pyroxenites), barren massifs (Sukhoberezovsky massif).

FACTUAL DATA

For identification modeling a spatial digital database of petrophysical parameters of crystalline and sedimentary rocks of the VKM territory was used, created on the basis of stock materials from different years. It presents the results of measurements of the physical properties of rock samples from core samples drilled during the study of the region. The database contains information on the density, speed of propagation of elastic waves, magnetic susceptibility and residual magnetization, polarizability, electrical resistivity and natural radioactivity of rocks — a total of about 90,000 definitions for 4400 wells (Muravina, Glaznev, 2014; Muravina, Zhavoronkin, 2014; Muravina et al., 2013). The database has an

open structure and is constantly updated due to measurements performing in the petrophysical laboratory of the Department of Geophysics, Voronezh State University.

The organization of the database in the format of a GIS project ensures accurate spatial reference of information, which allows it to be effectively used to solve various geological and geophysical problems. To perform this study, a sample of data for wells located within the Khopersky megablock VKM was formed from a single database. Then, for identification analysis, the results of petrophysical measurements were selected for wells that revealed intrusive rocks of a basite-hyperbasite composition, including intrusions of the mamonsky complex. For the formation of identification models, one of the wells was selected within the Nizhnemamonskoye deposit (well 500a), taken as the reference one (Fig. 1). This well is characterized by sufficient representativeness of petrophysical data (534 determinations performed on 107 core samples), as well as high degree of geological knowledge (Chernyshov, 1986; Chernyshova, 1999).

IDENTIFICATION MODELING
TECHNIQUE

The computational experiment was carried out using a program that implements the multi-row algorithm GMDH with combinatorial choice of model options (Muravina, Ponomarenko, 2016). According to the data from the reference well, for all petrographic rock types with representative samples of petrophysical data training and test sequences were generated. To select the optimal model, a regularity criterion was used, determined by the ratio:

$$cr = \frac{\|Y - Y_M\|^2}{\|Y_M\|^2}, \quad (3)$$

where Y — experimental values of the dependent variable, Y_M — model values of the dependent variable. In accordance with the principle of self-regulation, independent test sequence data were used to calculate the criterion. These data were not used to calculate the coefficients of model equations.

At the first stage of research, an attempt was made to obtain a generalized model equation linking the conditional petrographic index with petrophysical parameters and spatial attributes. However, it was not possible to obtain a model of good quality, which is probably due to a high degree of statistical non-uniformity of petrophysical data. At the second stage, identification modeling was performed for the most representative petrographic types of rocks. The density was chosen as the dependent variable, and the following parameters were used as variable-arguments: the propagation velocity of elastic waves, magnetic susceptibility, residual magnetization and polarizability, and also the depth of sampling.

IDENTIFICATION MODELING RESULTS

As a result of numerical modeling for the petrophysical parameters of the reference well, good quality identification equations for peridotites, pyroxenites and serpentinites, including ore ones, were obtained (Fig. 2).

All models are obtained at the first generation level and are determined by equation (1). Some characteristics of the identification models of the reference well are given in the table. Model equations

relate rock density (σ) to two variable arguments. For all models, the first and most significant factor is the propagation velocity of longitudinal elastic waves (V_p). The influence of the second factor is less significant. In three cases, the effect on the density of magnetic properties was revealed. For peridotites, this is the magnetic susceptibility (χ), in the case of pyroxenites and serpentinites, the second argument is the residual magnetization (J_r). For ore serpentinites, a statistical dependence was established with the velocity of longitudinal waves (V_p) and the depth of sampling (H).

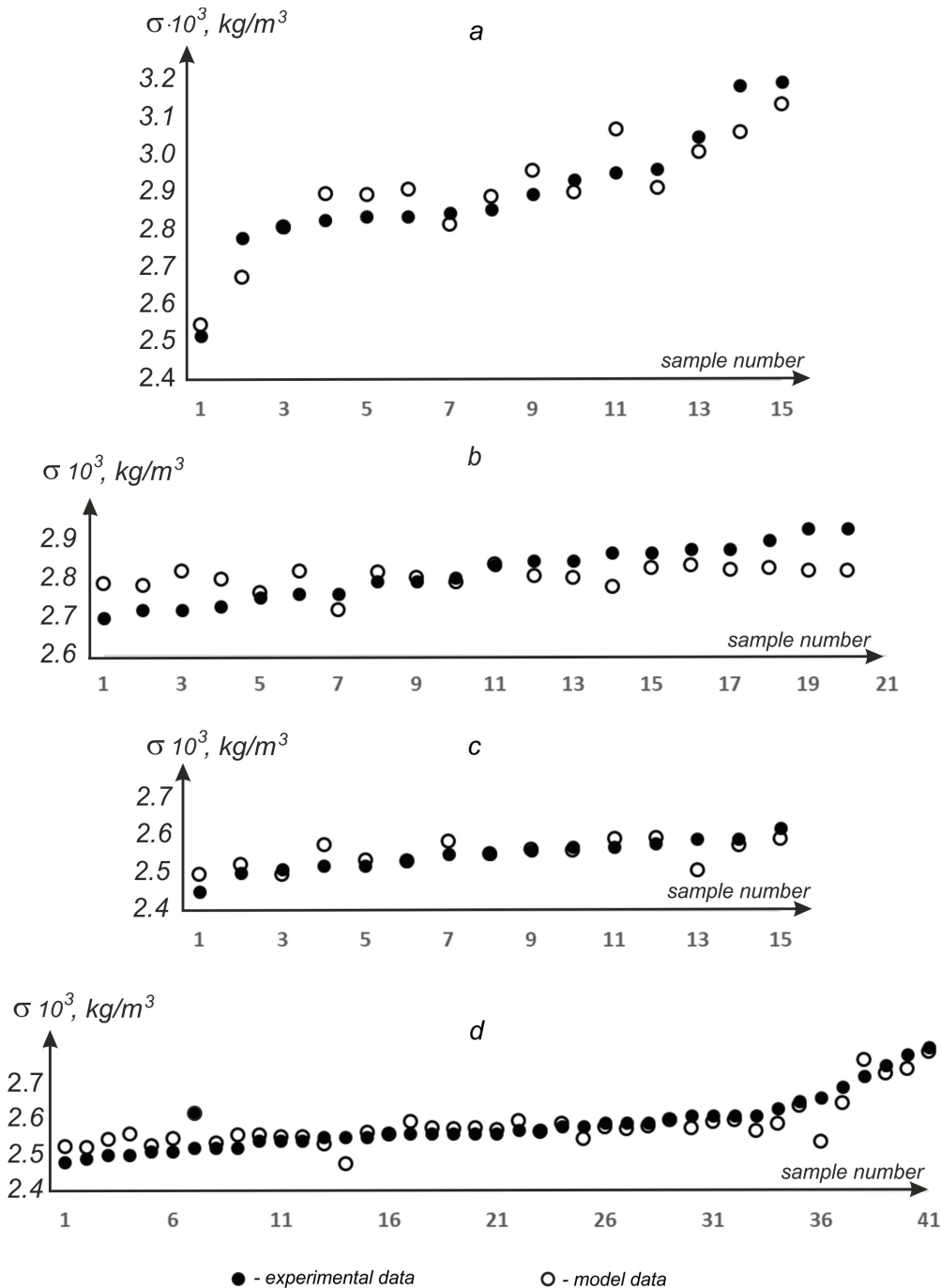


Fig. 2. The results of identification modeling for the rocks from the reference borehole: *a* — peridotites; *b* — pyroxenites; *c* — ore serpentinites; *d* — serpentinites.

The structure and set of parameters of model equations does not contradict the physical nature of the petrophysical characteristics. The close correlation between the density and velocity of rocks has been established by many researchers for different rocks and for different regions, including for the VKM (Glaznev et al., 2012). The presence in the models as the second arguments of the petromagnetic parameters or depth is also justified and may be associated with a change in the physical properties of the rocks during metamorphism.

The obtained identification equations of the reference well were applied to similar rocks of other (ordinary) wells located within the Khopersky megablock. For these wells, using model equations for each type of rock, the model values of the dependent variable (rock density) were calculated. In total, during the computational experiment, data on 30 wells were analyzed and 50 sets of input petrophysical parameters were tested.

The standard error of the correspondence of model values to the experimental ones for the control well is in the range (20–50) kg/m³ and does not exceed the standard deviation of the initial density arrays (table). On this basis, to assess the quality of modeling in conventional wells, it is customary to consider the threshold value of the standard error equal to 50 kg/m³.

The total length of the sequence for peridotites was 132 values for 14 wells. For 6 wells, the root-mean-square error of modeling the dependent variable does not exceed the threshold value.

The identification analysis procedure for pyroxenites involved data from 10 wells. The total length of the sequence of observations was 93 values. For 6 wells, the mean square error of the simulation also does not exceed the threshold value.

Model and experimental values of the density of serpentinite were compared for 20 wells and for 250 values. Positive results were obtained for 6 wells. Ore serpentinites were analyzed for 7 wells, the length of the overall sequence of test data was 114 values. In general, for 13 out of 30 wells, the standard error of the simulation did not exceed the threshold value when using at least one of the four variants of the models.

ANALYSIS OF THE RESULTS

Consider the wells with the best results of the identification modeling representing different intrusions of the mamonsky type (Fig. 1, 3).

For these wells, good convergence of the model and experimental data. The difference between the experimental and model density values in most cases is significantly less than the accepted threshold value.

Identification models of the reference borehole

Rocks	<i>n</i>	σ , ± kg/m ³	δ , ± kg/m ³	<i>cr</i>	Type of dependency
Peridotites	19	60	40	0.026	$\sigma = f(v, \chi)$
Pyroxenites	15	170	50	0.001	$\sigma = f(v, Jr)$
Ore serpentinites	16	50	20	0.007	$\sigma = f(v, H)$
Serpentinites	41	80	30	0.004	$\sigma = f(v, Jr)$

Note: *n* — the length of the observation sequences; σ — the standard deviation of the experimental density values; δ — the mean-square error of modeling; *cr* — an external criterion.

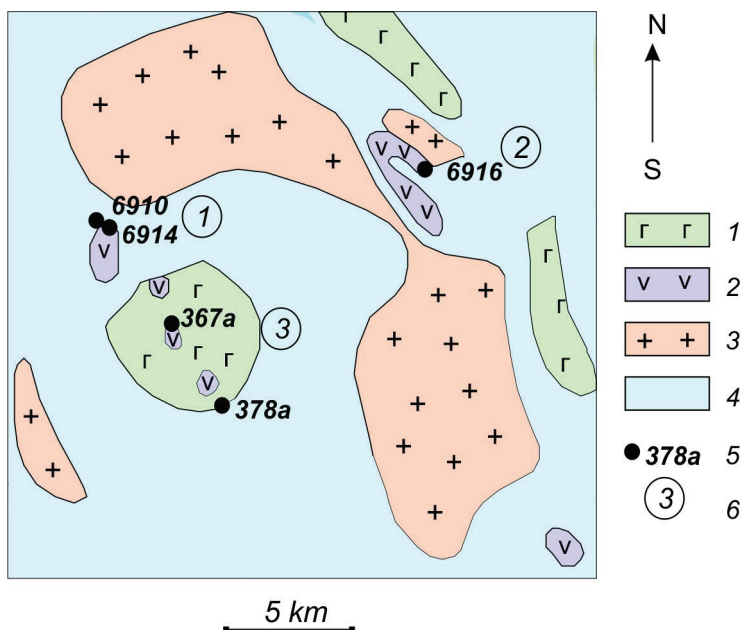


Fig. 3. Borehole location scheme with the best results of identification modeling: 1 — gabbroids from the Mamonsky complex; 2 — mafic-ultramafic rocks; 3 — granitoids from the Borovky complex; 4 — host rocks from the Vorontsovskaya series; 5 — boreholes and their numbers. Numbers in the circles denote: 1 — Astakhovskoye ore occurrence; 2 — Shishovskoye ore occurrence; 3 — Sukhoberezovskiy intrusive massif.

Such results were obtained for two or more types of rocks (Fig. 4, 5). All this with a high degree of certainty allows us to assume that the intrusions exposed by these wells are ore-bearing.

This assumption is also supported by the fact that all considered wells are located in close proximity to each other in the northwestern part of the Khopersky megablock (Fig. 1) and possibly belong to the same focus of magma generation. The reference well 500a (Nizhnemamonskoye deposit, Fig. 1) is located at a distance of 90–80 km in a southeast direction.

According to well-known geological data (Chernyshov, 1986; Cherny-shova, 1999), rocks uncovered by wells 6910 and 6914 are ore-bearing (Astakhovskoye ore occurrence), or potentially ore-bearing (Shishovskoye ore occurrence, well 6916). This is consistent with our results of identification modeling.

Wells 367a and 378a are located within the Sukhoberezhovskiy intrusive massif. On based previously performed studies it was classified as barren. However, taking into account the relatively small drilling depth of these wells (300–500 m), we can assume the presence of ore-bearing zones at great depths.

Thus, as a result of identification modeling of ultramafic-mafic intrusions of the mamonsky complex of the Voronezh crystalline massif, model equations are obtained, that make it possible to identify ore-bearing intrusions by a complex of petrophysical parameters.

CONCLUSIONS

The results of the performed identification analysis demonstrated the possibility of using the method of group accounting of arguments to solve the most

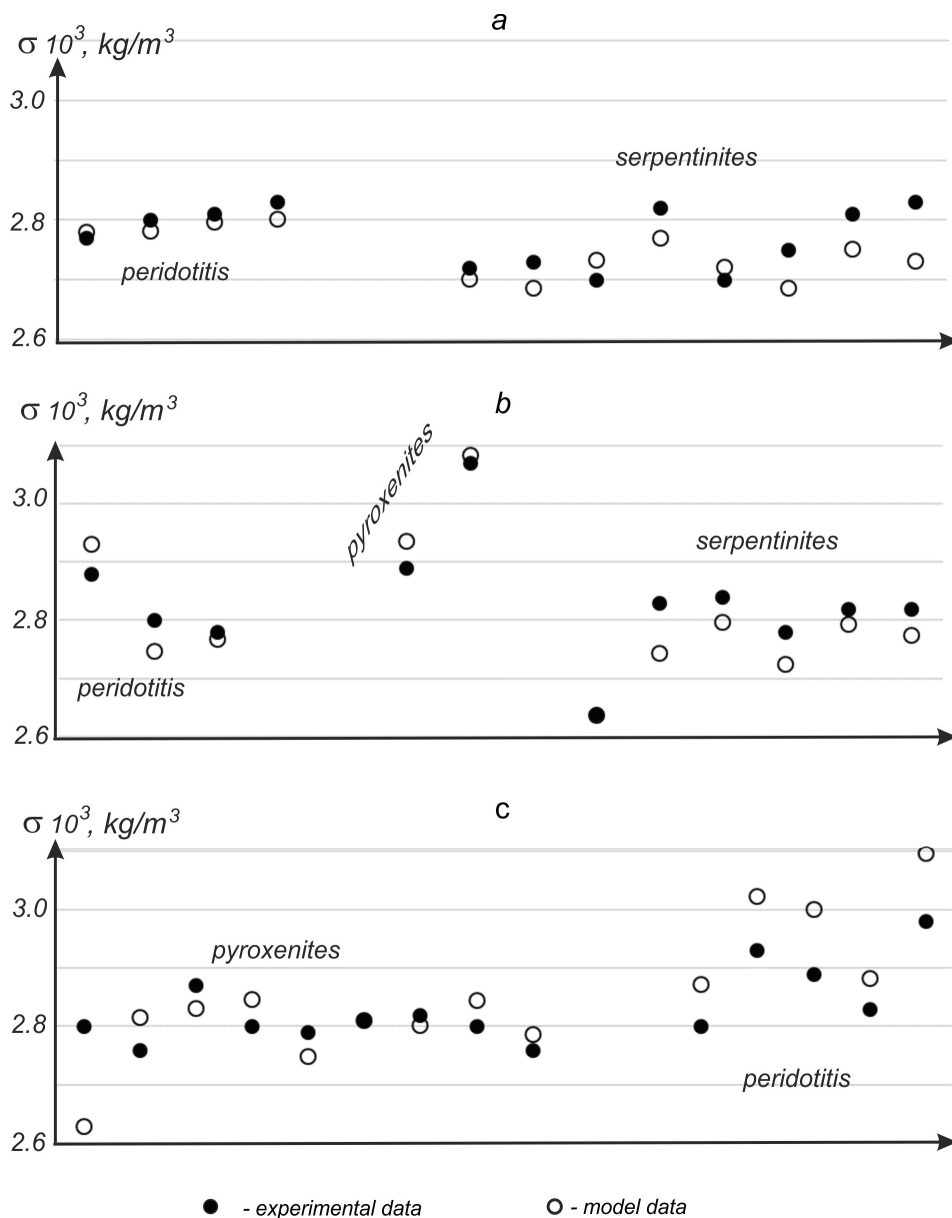


Fig. 4. The results of identification modeling: *a* — borehole 6910 (Astakhovskoye ore occurrence); *b* — borehole 6914 (Astakhovskoye ore occurrence); *c* — borehole 6916 (Shishovskoye ore occurrence).

IDENTIFICATION ANALYSIS

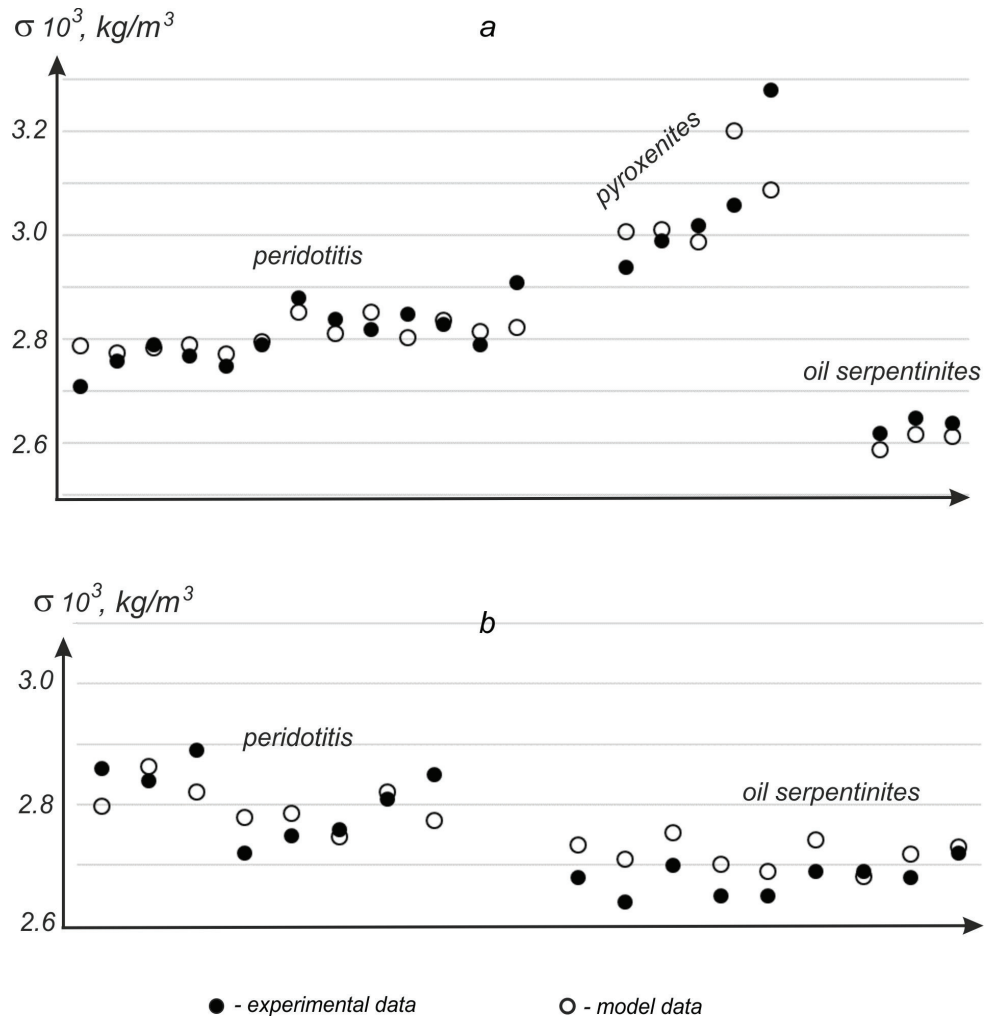


Fig. 5. The results of identification modeling: *a* — borehole 367a (Sukhoberezovsky intrusive massif); *b* — borehole 398a (Sukhoberezovsky intrusive massif).

important problem — the differentiation of coeval intrusions into ore and oreless ones.

GMDH allows the most efficient use of varied petrophysical data and spatial attributes, to reveal implicit relationships between the analyzed parameters and, as a result, to obtain an identification model as a unique characteristic of a geological object.

Thus, GMDH is an extremely promising tool for solving problems of geological mapping and, in particular, identification of objects of various genesis.

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References

- Antipov I.V.* Substantiation of a prediction criterion for sudden coal extrusions by the group method of data handling // *Fundamentalnye i prikladnye voprosy gornyh nauk*. 2017. T. 4. № 2. P. 7–12 (in Russian).
- Boyarinov Yu.G.* Postroenie modelej regionalnyh socialno-ekonomicheskikh sistem s pomoshchyu nejro-nechyotkogo metoda gruppovogo ucheta argumentov // *Sistemy upravleniya i informacionnye tekhnologii*. 2006. T. 24. № 2–1. P. 117–120 (in Russian).
- Glaznev V.N., Zhavoronkin V.I., Hovanskij N.E.* Korrelyatsiya skorosti i plotnosti porod Voronezhskogo kristallicheskogo massiva // *Voprosy teorii i praktiki geologicheskoy interpretatsii geofizi-cheskikh polej. Materialy 39-j sessii Mezhdunarodnogo nauchnogo seminara im. D.G. Uspenskogo. Voronezh: Nauchnaya kniga*, 2012. P. 71–75 (in Russian).
- Glaznev V.N., Mins M.V., Muravina O.M.* Density modelling of the Earth crust for central part of the East-European platform // *Vestnik KRAUNTs. Nauki o Zemle*. 2016. № 1(29). P. 53–63 (in Russian).
- Zhavoronkin V.I., Faustova YU.S.* Identification analysis of data on the electrical conductivity of the sedimentary case of the Voronezh crystalline massif // *XIX Mezhdunarodnaya konferenciya «Fiziko-himicheskie i petrofizicheskie issledovaniya v naukah o Zemle». Materialy konferencii. M.: IGEM RAN*, 2018. P. 120–123 (in Russian).
- Ivahnenko A.G.* Induktivnyj metod samoorganizatsii modelej slozhnyh sistem. Kiev: Naukova dumka, 1982. 296 p. (in Russian).
- Kalinina E.S.* Possibilities of the group method of data handling in problems of forecasting of safety of chemical productions // *Prirodnye i texnogenne riski (fiziko-matematicheskie i prikladnye aspekty)*. 2016. № 4 (20). P. 33–38 (in Russian).

- Muravina O.M.* Possibilities of the method of group accounting of arguments in the statistical processing of petrophysical data // *Vestnik Voronezhskogo gosudarstvennogo universiteta. Ser. Geologiya.* 2009. № 2. P. 150–110 (in Russian).
- Muravina O.M.* The method of group accounting of arguments in the analysis of geophysical data // *Geofizika.* 2012. № 6. P. 10–20 (in Russian).
- Muravina O.M.* Identification analysis petrophysical characteristics stick of sedimentary rocks of the Voronezh anteclise // *Vestnik KRAUNC. Nauki o Zemle.* 2013. № 2(22). P. 20–25 (in Russian).
- Muravina O.M., Glaznev V.N.* Structural-parametric models of petrophysical parameters sedimentary cover Voronezh anteclise // *Izvestiya SO RAEN. Irkutsk: Izd. IGTU,* 2014. № 1 (44). P. 81–87 (in Russian).
- Muravina O.M., Zhavoronkin V.I.* Magnetic susceptibility of the phanerozoic deposits of the Voronezh anteclise // *Vestnik KRAUNTs. Nauki o Zemle.* 2014. № 1(23). P. 79–88. (in Russian).
- Muravina O.M., Zhavoronkin V.I., Glaznev V.N.* Petrophysical characteristics of the sedimentary cover of the Voronezh anteclise // *Vestnik Voronezhskogo gosudarstvennogo universiteta. Ser. Geologiya.* 2013. № 1. P. 189–196.
- Muravina O.M., Ponomarenko I.A.* Features of application of the group method of data handling at identification modelling of geologic-geophysical data // *Vestnik Voronezhskogo gosudarstvennogo uni-versiteta. Ser. Geologiya.* 2016. № 2. P. 107–110 (in Russian).
- Skobelev D.O., Kovalenko V.P., Vybojchenko E.I.* Algoritmi formirovaniya ogranichitelnyx norm pokazatelej kachestva nefteproduktov s ispolzovaniem metoda gruppovogo uchyota argumentov (dalee - MGUA) // *Mir nefteproduktov. Vestnik neftyanyx kompanij.* 2015. № 1. P. 45–49 (in Russian).
- Starcev E.A.* Sintez klassifikatorov dlya prognoza professional'nyx zabolevanij na osnove metoda gruppovogo ucheta argumenta i nejrosetevogo modelirovaniya // *Energoberezhenie i effektivnost v texnicheskix sistemax. Materialy IV Mezhdunarodnoj nauchno-texnicheskoj konferencii studentov, molodyx uchenyx i specialistov. Tambovskij gosudarstvennyj texnicheskij universitet.* 2017. P. 519–520 (in Russian).
- Chernyshov N.M.* Tipy nikelenosnyh intruzij i medno-nikelevogo orudneniya Voronezhskogo massiva // *Sovetskaya geologiya.* 1986. № 12. P. 42–54 (in Russian).
- Chernyshova M.N.* Dajki mamonskogo nikelenosnogo kompleksa i ih sootnoshenie s orudneniem. Voronezh: Izd-vo VGU, 1999. 121 p. (in Russian).
- Shurygin D.N., Vlasenko S.V., Shastik D.S., Pozdeev I.P., Krotanok A.Yu.* Modelirovanie optimalnoj teoreticheskoy variogrammy moshhnosti plasta na osnove metoda gruppovogo ucheta argumentov // *Izvestiya vysshix uchebnyx zavedenij. Severo-Kavkazskij region. Seriya: Texnicheskie nauki.* 2014. № 4 (179). P. 76–78 (in Russian).
- Aksenova T.I., Tetko I.V., Volkovich V.V.* GMDH-type Neural Network in Quantative-Structure Activity Relationship Studis on the Internet, Modelling and simulation // *15th European Simulation Multiconference (ESM2001).* Prague, 2001. P. 685–689.
- Farrow S.J.* The GMDH algorithm of Ivakhnenko // *The American Statistician.* 1981. № 4(35). P. 210–215.
- Fernández F., Lozano F.H.* GMDH algorithms implemented in the intelligent identification of a bioprocess // *ABCM Symposium Series in Mechatronics.* 2010. V. 4. P. 278–287.
- Hiassat M., Abbod M.F., Mort N.* Using Genetic Programming to Improve the Group Method of Data Handling in Time Series Prediction // *Statistical Data Mining and Knowledge Discovery. Chapman&Hall/CRC,* 2004. P. 282–293.
- Kondo T. Pandya A.S., Zurada J.M.* GMDH-type neural networks with a feedback loop and their application to nonlinear system identification // *Smart Engineering System: Neural Networks, Fuzzy Logic, Evolutionary Programing, Data Mining, and Rough Sets. ASME Press.* 1999. V. 9. P. 117–124.
- Muravina O.M., Glaznev V.N., Zhavoronkin V.I., Mints M.V.* Reflection of the Petrophysical Basement Rocks Models in Geophysical Fields // *Practical and Theoretical Aspects of Geological Interpretation of Gravitational, Magnetic and Electric Fields. Springer Proceedings in Earth and Environmental Sciences – Springer Nature Switzerland AG,* 2019a. P. 49–53.
- Muravina O.M., Davydova E.I., Ponomarenko I.A.* Possibility of identifi-cation of modeling in complex analysis geological and geophysical data / *Practical and Theoretical Aspects of Geological Interpretation of Gravitational, Magnetic and Electric Fields. Springer Proceedings in Earth and Environmental Sciences – Springer Nature Switzerland AG,* 2019b. P. 157–162.
- Muravina O.M., Glaznev V.N., Zhavoronkin V.I., Mints M.V.* Reflection of the Petrophysical Basement Rocks Models in Geophysical Fields // *Practical and Theoretical Aspects of Geological Interpretation of Gravitational, Magnetic and Electric Fields. Springer Proceedings in Earth and Environmental Sciences – Springer Nature Switzerland AG,* 2019b. P. 49–53.
- Upadhyaya B.R., Lu B.* Data Mining for Monitoring Plant Devices Using GMDH and Pattern Classification // *Statistical Data Mining and Knowledge Discovery. Chapman&Hall/CRC,* 2004. P. 294–304.
- Yurachkovsky Y.P.* Restoration of Polynomial Dependencies Using Self-Organization // *Soviet Automatic Control.* 1981. № 14. P. 17–22.