Проведено варіограмний аналіз основних показників якості каолінів. Розроблено методику геостатистичного підрахунку запасів Велико-Гадоминецького родовища первинних каолінів із врахуванням сортової диференціації для підвищення ефективності управління якістю сировини. Встановлено основні типи взаємозв'язків між показниками якості каолінів. Визначено об'єми покладу каоліну Велико-Гадоминецького родовища за промисловостями і сортами. Запропоновано методику оцінки похибки визначення обсягів виконаних робіт на родовищі для підвищення ефективності управління процесами розробки покладів

Ключові слова: геометризація, геостатистичний аналіз, каоліни, білизна каолінів, сортова диференціація, варіограмний аналіз, метод Сімпсона, управлыння, управління якістю, технологічні процеси

Проведен вариограммный анализ основных показателей качества каолинов. Разработана методика геостатистического подсчета запасов Велико-Гадоминецкого месторождения первичных каолинов с учетом сортовой дифференциации для повышения эффективности управления качеством сырья. Определены объемы залежи каолина Велико-Гадоминецкого месторождения по промышленностям и сортам. Предложена методика оценки погрешности определения объемов выполненных работ на месторождении для повышеня эффективности управления качеством разработки месторождений

Ключевые слова: геометризация, геостатистический анализ, каолины, белизна каолинов, сортовая дифференциация, вариограммный анализ, метод Симпсон, управление качеством, технологические процессы

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A PROCEDURE FOR MODELING THE DEPOSITS OF KAOLIN RAW MATERIALS BASED ON THE COMPREHENSIVE ANALYSIS OF QUALITY INDICATORS

R. Sobolevskyi
PhD, Associate Professor*
E-mail: rvsobolevsky@rambler.ru
O. Vaschuk
Assistant*
O. Tolkach
PhD**
E-mail: oltolkach@gmail.com
V. Korobiichuk
PhD, Associate Professor**
E-mail: kgtkvv2@rambler.ru
V. Levytskyi
PhD, Associate Professor*
E-mail: v.levytsky@ztu.edu.ua
*Department of mine surveying***
Department of Mining named after prof. Bakka M. T.*
***Zhytomyr State Technological University
Chernyahovskoho str., 103, Zhytomir, Ukraine, 10005

1. Introduction

Ukraine possesses significant reserves of kaolin that make up 6.3 % of the world (14.8 billion tonnes) [1] and about 70 % of the reserves of the CIS countries (1.4 billion tonnes) [2]. Primary kaolins have been applied in 8 sectors of industry in Ukraine, which are characterized by a considerable number of varieties [3].

An important task at the enterprises that extract and process kaolin is determining its whiteness, which characterizes the degree of approximation to white by the strength of its brightness, high scattering capacity and minimal color tone [4]. Given that the kaolin grade depends on whiteness, the accuracy of its assessment and control over the quality of raw materials, based on its spatial distribution, which is executed during calendar planning of mining operations will determine economic efficiency of the work of an enterprise. That is why development of a procedure for objective and productive determining the whiteness of primary kaolins, which would combine high productivity, affordable price and permissible accuracy, is an important scientific-applied task.

2. Literature review and problem statement

It should be noted that the issue of determining the whiteness of primary kaolins is insufficiently investigated in scientific studies. It is linked to a rather insignificant amount of the examined objects and stability of procedures for determining this indicator. However, for a large number of enterprises, in connection with a significant rise in the productivity of certain technological processes to ensure the efficiency of quality control, a very important task is to improve productivity and reliability in the evaluation of whiteness. Given the fact that whiteness as a quality indicator is employed in various industries, it is advisable to perform an analysis of the innovative component of the results of research. Thus, in article [5], author designed a whiteness grading scale Wiso, which is applied to assess the level of quality of porcelain products. A technology was also proposed to build expert systems to identify the products and perform multi-dimensional graduation of information on measurements by quantitative and qualitative scales in order to compare porcelain goods. Paper [6] proposed to leave in the optical-spectral sensor for measurement of whiteness one measuring channel at wavelengths in the violet-blue region of the spectrum. It was proven that the use of additional optical channels at wavelengths λ=630 nm and λ=1100 nm makes it possible to partially compensate for the effect of some external factors that distort the value of actual whiteness. Scientific studies [7–9] addressed the use of color coordinate systems for the optimization of processes to control product quality. [7] designed a technique for determining color coordinates of physiological system based on processing the results of experimental research of detection thresholds of monochromatic radiation against a white background. Author of [8] designed a method of modeling a digital image represented in the coordinates of the color model HSL, using weighted sums of solutions to the Pearson differential equation, which enables to formalize a model parameters with indicators of quality of a bakery product, which provides the possibility to determine color parameters of quality of bakery products using the method of a digital image analysis to create automated control systems in bakery production. Paper [9] proposed a device based on the spectral-colorimetric method to measure coordinates of color and chromaticity. Two schemes of colorimeters are suggested that implement the proposed spectral-colorimetric method.

Research into geospatial variability of physical-chemical properties of a deposit, approaches for quality control over raw materials and the efficiency of implementation of certain technological processes of mining and enrichment of kaolins are tackled in articles [10–16]. Paper [10], in particular, considered a combination of geophysical and geostatistical methods to determine capacity of the clay deposits in the Edofe deposit (Southwestern Nigeria). The obtained results made it possible to considerably improve efficiency of mathematical modeling of the form of a deposit based on using, as a theoretical model, a spherical variogram in combination with kriging. Article [11] performed a geostatistical analysis in order to improve effectiveness of the quality control process when planning mining works for the conditions of deposit Rosa Porrino (Pontevedra, Spain). This analysis was conducted using a variogram analysis and composition kriging employing geostatistical tools of the ArcGIS software (USA).

To control the quality of raw materials, which is characterized by a large number of quality indicators that are included in the objective function, or used as limiting factors, it is advisable to use integrated indicators. [12] presented such indicators as: indices for selecting the models of variograms, index of the weighted least squares, a Cressy indicator, index of selection quality (applied in the Variowin software (USA)), the Akaike information criterion. Method of cross-checking for the estimation of the values of parameters is considered in [13] and is used in the software ArcGIS 10.1 [14]. It should be noted that a large number of integrated indicators makes it difficult to substantiate the effectiveness of their application; in addition, they do not provide a possibility to take into account the peculiarities in the processes of quality control over primary kaolins. Therefore, it is a relevant task to substantiate aprroaches to quality control based on the use of indicators that will be implemented based on geostatistical modeling of geospatial variability of quality indicators.

The next component in the quality control process effectiveness is a reliability of the estimation of volumes of planned and executed work. The basis for the implementation of this function is a mathematical modeling of the form of a deposit to control the processes of extracting and mining operations at a separate mining enterprise. Article [15] outlines the features in the development of software for operational calculation of reserves in the assigned contours of mining operations. Paper [16] considered creation of digital models of the shape of objects that are based on the use of the algorithm, underlying which are the elements of a Delaunay triangulation. The applied research results can be used to develop a program of construction of digital models of the shape of a deposit to realize optimization models of performing separate technological operations.

3. The aim and objectives of the study

The studies we conducted set the goal to develop an effective procedure for the geometrization of deposits of kaolins based on an integrated consideration of quality indicators applying a geostatistical analysis to improve efficiency of the raw materials quality control processes.

To accomplish the set goal, the following tasks had to be solved:

– to devise a procedure for determining the whiteness of primary kaolins and to establish main types of interrelations between quality indicators of kaolins;

– to improve effectiveness of mathematical modeling of a geospatial variability of quality indicators in order to control technological processes of extraction and processing of primary kaolins;

– to improve efficiency of calendar planning of technological processes by modeling the errors in determining the volumes of work performed in the fields of primary kaolins.

4. Methods and materials for examining quality indicators of deposits of primary kaolins

A procedure for determining the whiteness of primary kaolins implies the following. One selects samples in advance in the career with the reference coordinates determined by the tacheometer 4Ta5. Raw kaolin is transformed into powder by wet milling in a planetary mill for 1–2 h (main milling parameter is a residual in the 80-μm sieve that does not exceed 1 %). Next, the ground suspension is dried in a drying chamber until reaching constant weight at a temperature of 100±5 °C (one-time drying). At such temperature, drying does not affect the structure of the clay component. Such temperature affects the physically bound water only and does not in any way destroy the chemically bound water and the structure of the clay body itself. Dried conglomerates are ground into powder using a rolling pin. In order to prepare a sample tablet to determine whiteness, a sample of 22 g is selected. Next, the bulk is pressed into a mould with a diameter of 50 mm at pressing effort 10 t with curing under maximal force for 30 s. An important parameter of the pressed tablet is roughness and defectiveness of the sample surface.

Most of the devices that are used for determining the whiteness at enterprises are often characterized by low speed of determining the whiteness of a sample and an error in determining the whiteness caused by a human factor. These devices provide for a minimal automation of the measurement process. Modern instruments are characterized by high accuracy of determining the whiteness, speed, but at the same time, by high price. The working principle of modern instruments for determining the whiteness is based on measuring illuminance, which is created on a photosensor, and illuminance that is created on a photosensor in the reference channel. Next, they calculate the ratio of the results obtained in the two channels. Based on the working principle of existing technologies to determine the whiteness, they examined the possibility of using a tablet scanner with subsequent processing of color coordinates of image pixels to define whiteness of the sample [17].

Scanning the samples of kaolin was conducted using the flatbed scanner Epson Perfection V200 Photo (Japan). Samples of kaolin in the form of compressed tablets with a diameter of 50 mm are arranged on the scanning surface of the scanner in the amount of 20 pieces. Next, we perform scanning of the same samples of kaolin with a resolution from 300 to 1800 pixels per inch at step 100. Next, we cut out separate samples of kaolin from the scanned image the size of format A4, and saved each as a separate umage. The next step was to upload the images of the samples in the "Whiteness" software. The software determined the value of whiteness by the RGB color coordinates. At the next stage, we computed actual value of whiteness according to a previously defined regression equation.

At present, there are a large number of color models, such as CMYK, RGB, Lab, HSB, XYZ, CMY, xyY, LCH_{ab}, Luv, LCH_{uv}. Based on [18–22], in order to process the scanned image, we chose the RGB color model. Whiteness W of the image of the scanned sample is proposed to calculate by formula (1):

$$W=\left(\frac{\sum_{i=1}^{n}\left(\frac{1}{3}R+\frac{1}{3}G+\frac{1}{3}B\right)\cdot k}{\sum_{J=1}^{k}\left(R_{max}+G_{max}+B_{max}\right)\cdot n}\right)\cdot 100\ \%, \qquad (1)$$

where R, G, B are the values of color coordinates in the RGB system; R_{max}, G_{max}, B_{max} are the maximal values of color coordinates; k is the number of elements in a system of color coordinates; n is the number of pixels whose whiteness is determined.

Correlation field of dependence of actual value of whiteness on the whiteness, defined by the color RGB coordinates, is shown in Fig. 1.

Using the obtained values of whiteness, we determined coefficient of linear pair correlation r_{xy}=0.81 and coefficient of determination R^2=0.64. The linear pair regression equation takes the form: $\hat{y}=1{,}8108x-88{,}942$.

Effectiveness of the proposed procedure for determining the whiteness of kaolin will be determined by performance, which can be determined by formula (2):

$$\Pi=\frac{60\cdot N_{sm}}{t_{ar}+t_{ss}+t_{cr}+t_{ls}+t_{pi}}\left(\frac{\text{piece}}{\text{min}}\right), \qquad (2)$$

where N_{sm} is the number of samples, pcs.; t_{ar} is the time needed to arrange the samples in a scanner, s; t_{ss} is the time needed to scan the samples, s; t_{cr} is the time needed to crop the images of the samples from the scanned image, s; t_{ls} is the time needed to up load to the software, s; t_{pi} is the time needed to process images by the software.

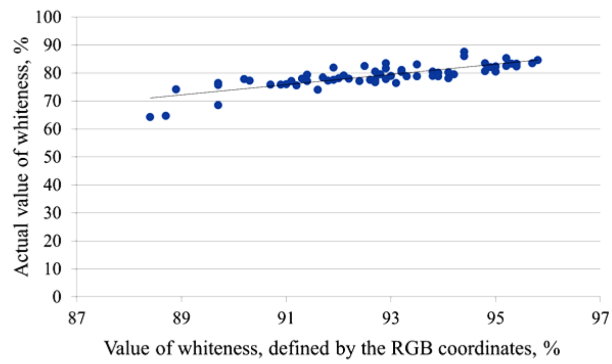


Fig. 1. Correlation field of dependence of actual value of whiteness on the whiteness, defined by the RGB coordinates

When analyzing Table 1, 600 ppi was selected as optimal resolution in the settings of the scanner. Scanning with such resolution takes a relatively little time, the scanned image takes up little space on the disk. The number of pixels in the image of one scanned sample, which is over 720000, is sufficient for statistical processing. Productivity of determining the whiteness in this case is 5.1 samples per minute.

Table 1

Combined settings of sample scanning

Number of pixels per inch (ppi)	Scanning time, s	RGB whiteness, %	Actual whiteness, %	Size of one sample, Mb	Maximal number of samples per one scanning, pcs.	Processing time of one sample by software, s	Productivity, pcs/min
300	11	93.7	80.9	0.5	20	0.9	7.0
400	14	93.8	81.1	0.9	20	1.5	6.5
500	26	93.7	80.9	1.4	20	2.3	5.6
600	26	93.7	80.9	2.1	20	3.4	5.1
700	72	93.8	81.1	2.7	20	4.3	4.0
800	76	93.7	80.9	3.5	20	5.6	3.6
900	96	93.7	80.9	4.9	20	7.8	3.1
1000	96	93.7	80.9	5.4	20	8.6	2.9
1100	96	93.7	80.9	6.3	20	10.0	2.7
1200	96	93.7	80.9	8.3	20	13.1	2.4
1300	237	93.9	81.3	9.8	15	15.5	1.6
1400	237	93.9	81.3	10.7	15	16.9	1.5
1500	236	94	81.5	13.6	15	21.5	1.3
1600	237	93.9	81.3	15.1	15	23.8	1.3
1700	322	93.9	81.3	16.4	15	25.9	1.1
1800	322	93.9	81.3	17.9	10	28.2	0.9

When choosing settings of the scanner, it is necessary to specify that such parameters as sharpening, removal of raster, restoring color, background correction, removal of defects and other options that may in any way change the original image, must be disabled.

The above-described procedure formed the basis for the creation of algorithm of the software “Whiteness” for determining the whiteness of kaolin using the scanned image of a sample. The source code of software is written in the high-level programming language Python.

Given the main trends in the development of procedures for the geometrization of qualitative indicators of a deposit, it is advisable to accept geostatistical methods of evaluation of spatial variability of quality indicators as the basis for the development of procedure of multifactor geometrization.

The studies were performed based on data of geochemical analysis of the samples selected from 196 wells drilled at the stage of preliminary exploration of a field. We chose a process of evaluation of a geospatial variability of quality indicators of Veliko Gadominetsky deposit as the examined object [23, 24].

Block diagram of algorithm’s operation in the software “Whiteness” is shown in Fig. 2.

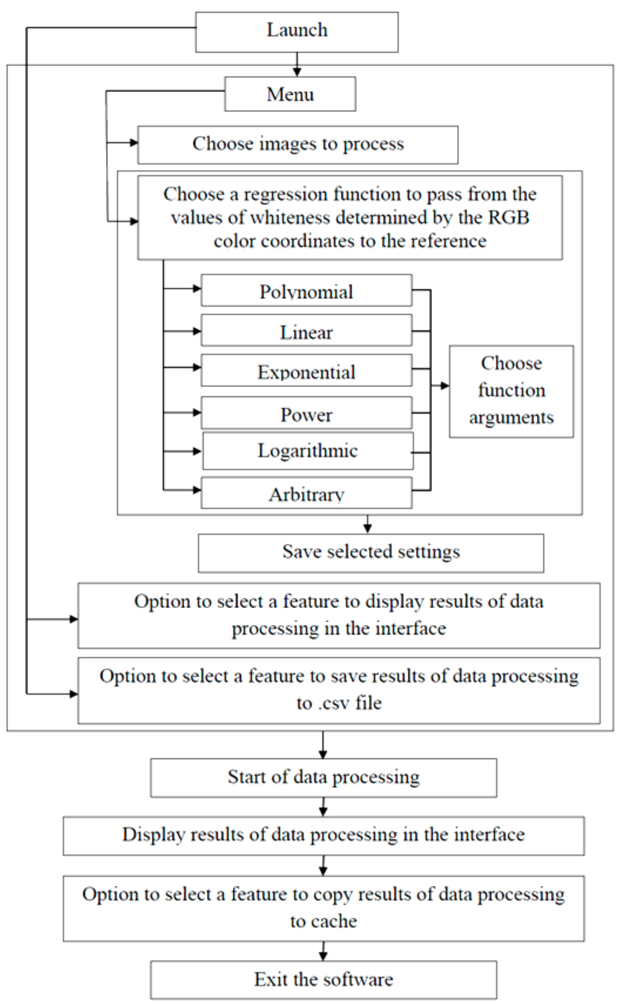


Fig. 2. Block diagram of determining the whiteness in the software “Whiteness”

At direct selection of the form and parameters of the model, it is necessary to assess its quality, which is determined by proximity to the experimental variogram – visual similarity [25–27]. The optimal model of variogram was determined from the following series of known types: spherical, exponential, Gaussian, logarithmic, cubic, quadratic, power, penta spherical, rational-quadratic, nugget effect (Table 2). In the course of present study, we examined the values of magnitude of nugget effect C_0 (Table 3), Sill (Table 4), Range (Table 5). We also investigated the value of deviation area of the points of experimental variogram from the theoretical (Table 6) and the value of a plane criterion (Table 7). Variograms were constructed taking into account main directions with a step in search angle 22.5°.

Table 2

Values of the plane criterion for different models along one common direction

No. of entry	Variogram model	C_0	Scale	Length (A)	Area, un.sq	Plane criterion
1	Spherical	0.015	0.1240	688	804.00	1.87
2	Exponential	0.013	0.1280	295	674.32	1.57
3	Gaussian	0.019	0.1230	350	863.80	2.01
4	Logarithmic	0.020	0.0387	45	430.21	1
5	Cubic	0.018	0.1215	805	883.16	2.05
6	Quadratic	0.011	0.1290	797	786.11	1.83
7	Power	0.006	0.1190	810	469.62	1.09
8	Penta spherical	0.012	0.1260	842	801.43	1.86
9	Rational-quadratic	0.018	0.1290	252	691.51	1.61
10	Nugget effect	0.019	0.1120	145	1209.68	2.81

Table 3

Values of magnitude of nugget effect C_0 at distribution along directions and variogram models

Model	Parameter	Directional angle, degrees								Mean
		90	67.5	45	22.5	0	337.5	315	292.5	
Gaussian	C_0	0.002	0.001	0.008	0.019	0.004	0.024	0.025	0.023	0.013
Exponential		0.001	0.002	0.003	0.013	0.003	0.011	0.024	0.022	0.01
Logarithmic		0.007	0.005	0.019	0.02	0.003	0.02	0.021	0.023	0.015
Power		0.002	0.001	0.001	0.006	0.006	0.001	0.001	0.002	0.003
Spherical		0.005	0.003	0.004	0.015	0.005	0.019	0.018	0.021	0.011

Table 4

Values of magnitude Sill at distribution along directions and variogram models

Model	Parameter	Directional angle, degree								Mean
		90	67.5	45	22.5	0	337.5	315	292.5	
Gaussian	Sill	0.106	0.128	0.13	0.123	0.129	0.09	0.075	0.073	0.107
Exponential		0.117	0.138	0.144	0.128	0.142	0.11	0.075	0.07	0.116
Logarithmic		0.033	0.044	0.043	0.039	0.04	0.033	0.025	0.022	0.035
Power		0.095	0.115	0.127	0.119	0.117	0.108	0.093	0.091	0.108
Spherical		0.103	0.125	0.131	0.124	0.126	0.097	0.084	0.074	0.108

Table 5

Values of magnitude Range at distribution along directions and variogram models

Model	Parameter	Directional angle, degree								Mean
		90	67.5	45	22.5	0	337.5	315	292.5	
Gaussian	Range	394	362	375	350	337	254	283	302	332
Exponential		384	384	342	295	358	280	216	216	309
Logarithmic		51	62	61	45	38	49	41	39	48
Power		854	891	852	810	782	833	867	794	835
Spherical		897	904	705	688	701	694	602	635	728

Table 6 gives values of deviation area of the points of experimental variogram on the theoretical at distribution along directions and variogram models. Table 7 gives values of the plane criterion at distribution along directions and variogram models. Table 8 gives quality evaluation of the variograms of different models along main directions.

Table 6

Values of deviation area of the points of experimental variogram on the theoretical at distribution along directions and variogram models

Model	Parameter	Directional angle, degree								Mean
		90	67.5	45	22.5	0	337.5	315	292.5	
Gaussian	Deviation area (un.sq.)	2254	3267	3312	2267	3489	2336	2274	1904	2638
Exponential		1685	2585	2419	2178	3083	2158	2150	1869	2266
Logarithmic		1502	2128	1833	1383	2557	1847	1861	1635	1843
Power		1703	2327	1704	1496	2697	1803	1750	1610	1886
Spherical		2143	3133	3134	2578	3398	2378	2197	1811	2597

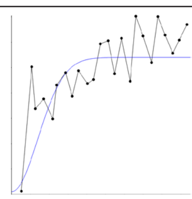
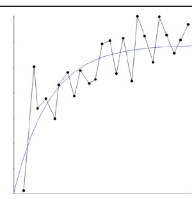
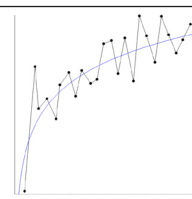
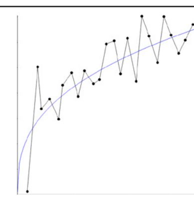
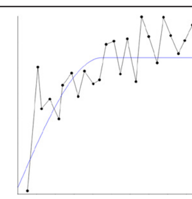
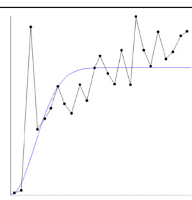
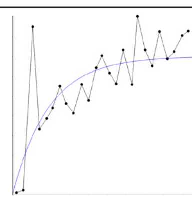
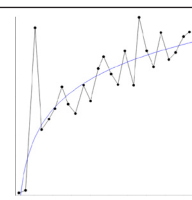
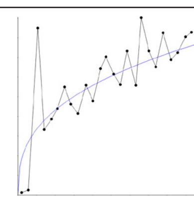
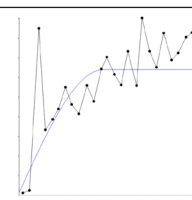
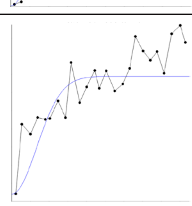
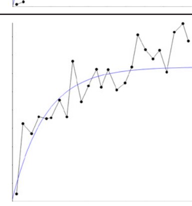
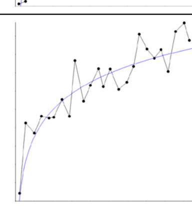
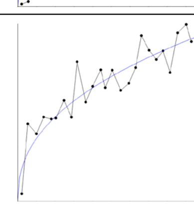
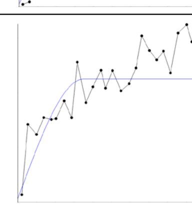
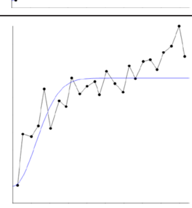
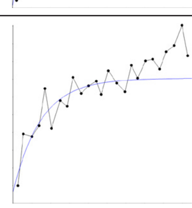
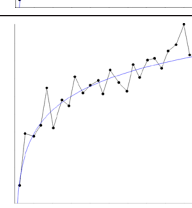
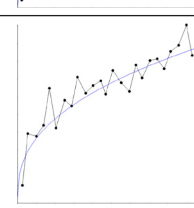
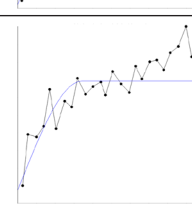
Table 7

Values of the plane criterion at distribution along directions and variogram models

Model	Parameter	Directional angle, degree								Mean
		90	67.5	45	22.5	0	337.5	315	292.5	
Gaussian	Area, reduced to the lowest value	1.50	1.54	1.81	1.64	1.36	1.26	1.22	1.16	1.44
Exponential		1.12	1.22	1.32	1.58	1.21	1.17	1.16	1.14	1.24
Logarithmic		1	1	1	1	1	1	1	1	1
Power		1.13	1.09	0.93	1.08	1.05	0.98	0.94	0.98	1.02
Spherical		1.43	1.47	1.71	1.86	1.33	1.29	1.18	1.11	1.42

Table 8

Quality evaluation of the variograms of different models along main directions

Azimuth	Gaussian	Exponential	Logarithmic	Power	Spherical
1	2	3	4	5	6
90°					
67.5°					
45°					
22.5°					

Continuation of Table 8

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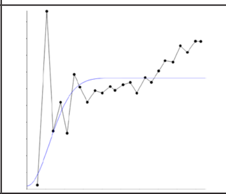
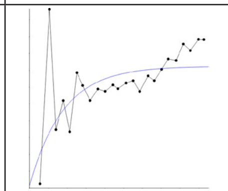
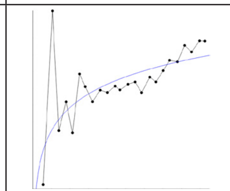
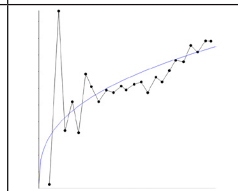
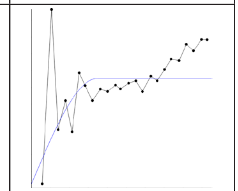
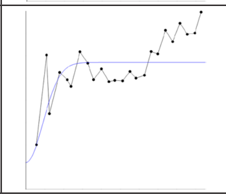
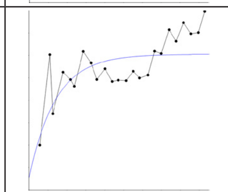
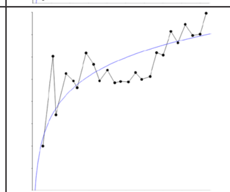
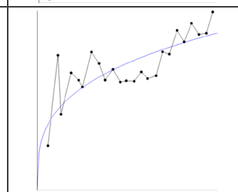
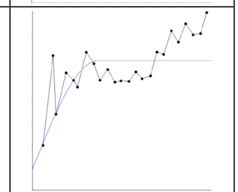
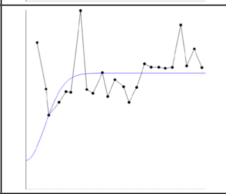
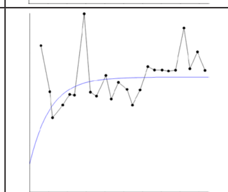
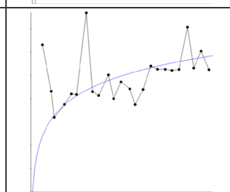
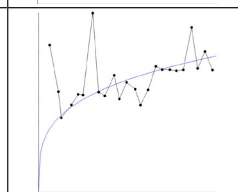
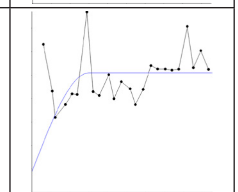
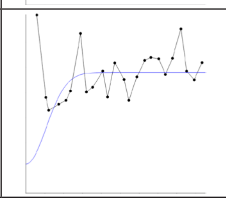
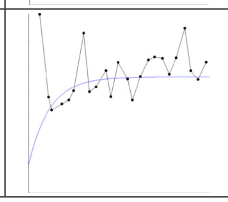
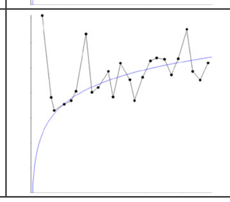
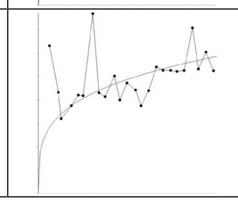
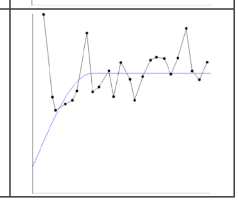
0°					
337.5°					
315°					
292.5°					

For the purpose of analysis and spatial prediction of quality indicators of kaolin originated from the Velyko-Gadominetsky deposit, we performed a regression analysis of data. With regard to the above outlined studies, we selected an exponential form as a theoretical continuous model of a variogram.

In the course of execution of a variogram analysis, we determined a coefficient of anisotropy and a direction of the ellipsoid axis of anisotropy for the content of Fe_2O_3, TiO_2 and whiteness, respectively. We also received maximal values of variances at which the variogram passes to a plateau, as well as the length of data autocorrelation. Construction of variograms was carried out taking into account the main directions at a step of search angle 22.5°.

Results of the construction of a variogram (Fig. 3, *a* – Fe_2O_3) (Fig. 4, *a* – TiO_2), (Fig. 5, *a* – whiteness) and anisotropy ellipsoid (Fig 3, *b* – Fe_2O_3) (Fig. 4, *b* – TiO_2), (Fig. 5, *b* – whiteness) are shown in Fig. 3.

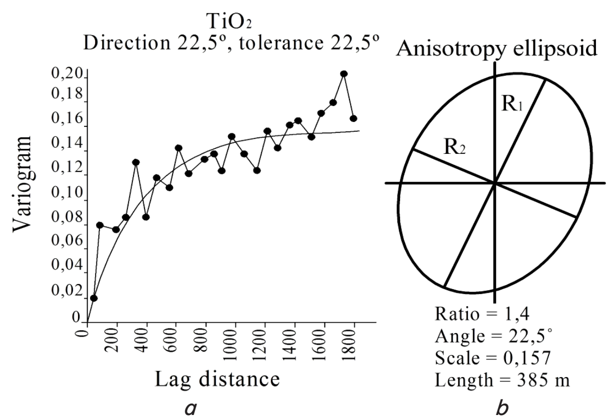


Fig. 4. Result of construction: *a* — variogram of the TiO_2 content (exponential form); *b* — anisotropy ellipsoid of the TiO_2 content

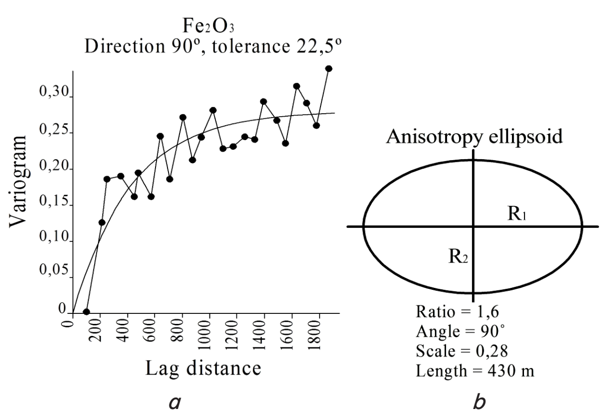


Fig. 3. Result of construction: *a* — variogram of the Fe_2O_3 content (exponential form); *b* — anisotropy ellipsoid of the Fe_2O_3 content

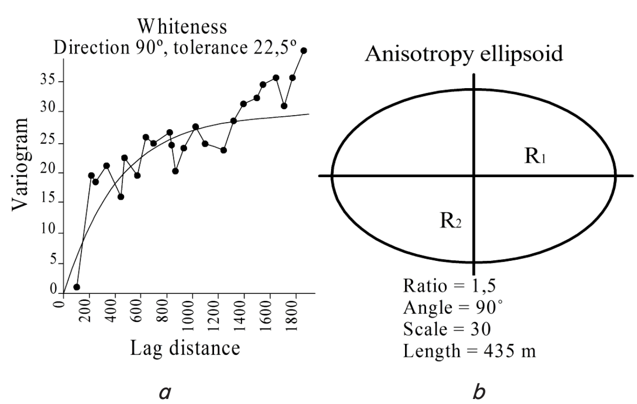


Fig. 5. Result of construction: *a* — variogram of the whiteness content (exponential form); *b* — anisotropy ellipsoid of the whiteness content

Given the results of previous studies [3, 28] and main approaches to a geostructural analysis [15, 16, 29, 30], we devised a procedure for geostatistical calculation of reserves. In addition, we calculated the volume of Velyko Gadominetsky deposit of primary kaolins considering a grade differentiation. To calculate the volume by a geostatistical method, we employed the software Surfer 11.2.

Construction of a map of isolines of the content of whiteness demonstrated that the content of whiteness over the entire deposit area meets technical requirements of chemical industry.

Block diagram of geostatistical calculation of volume is shown in Fig. 6.

In order to calculate the amount of kaolin by the industry grades, first we outlined the areas within which kaolin meets technical requirements in terms of the content of quality indicators. For example, to calculate the volume of kaolin of the grade "KES-35", we first outlined the area taking into account an anisotropy coefficient in line with technical requirements. Next, we outlined area by the TiO_2 content (Fig. 7, *a*), and then by the content of Fe_2O_3 (Fig. 7, *b*).

As a result of overlap of the planes with quality content of TiO_2, Fe_2O_3 and the whiteness of kaolin of the grade "KES-35", there occurred a region, within which kaolin meets technical requirements simultaneously by all quality indicators (Fig. 7, *c*). Interpolation of data grid by the wells was conducted using block kriging, based on empirical semi-variograms approximated by regression lines.

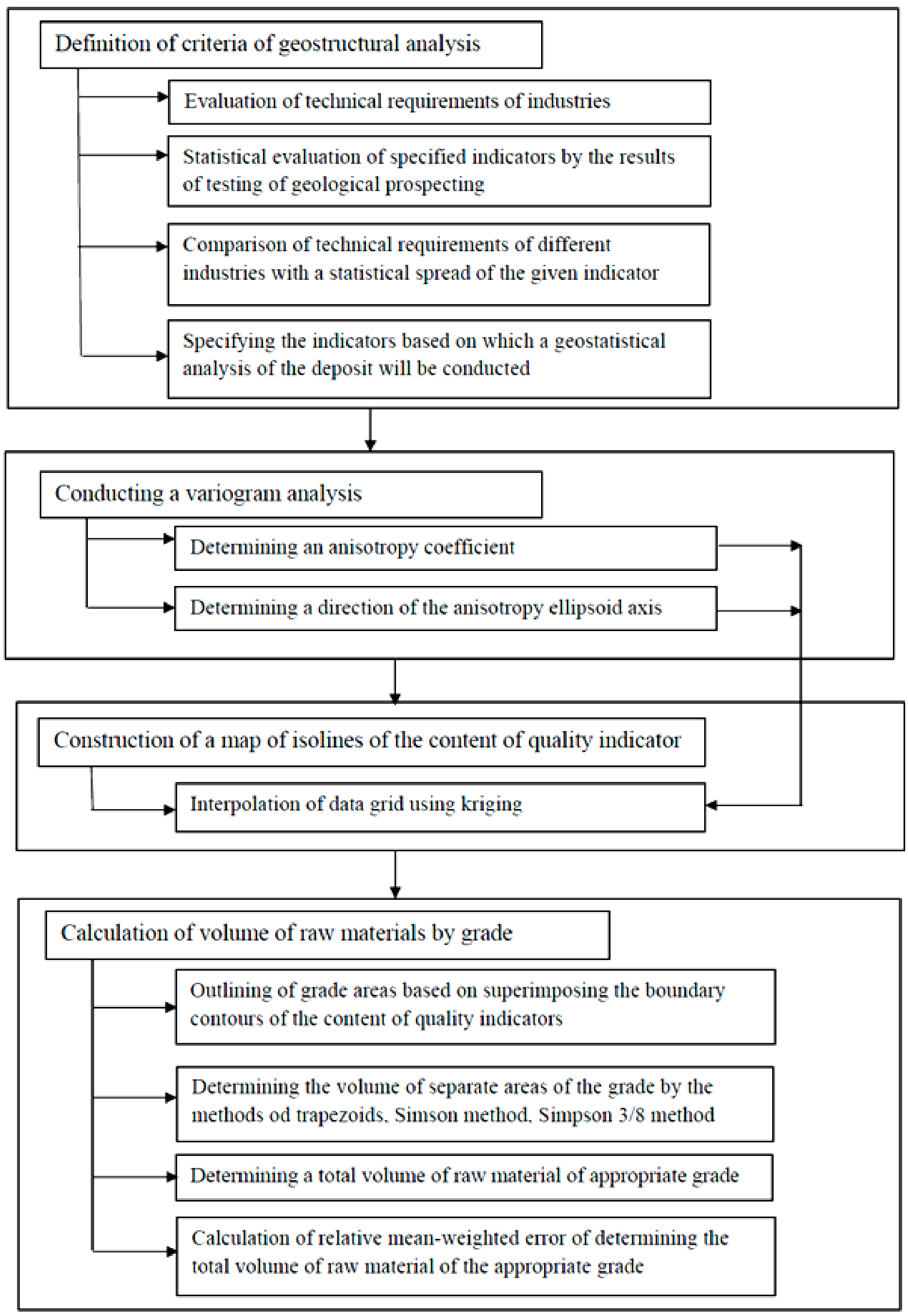


Fig. 6. Structural scheme of the procedure of geostatistical calculation of reserves of Velyko-Gadominetsky deposit of primary kaolins with a consideration of grade differentiation

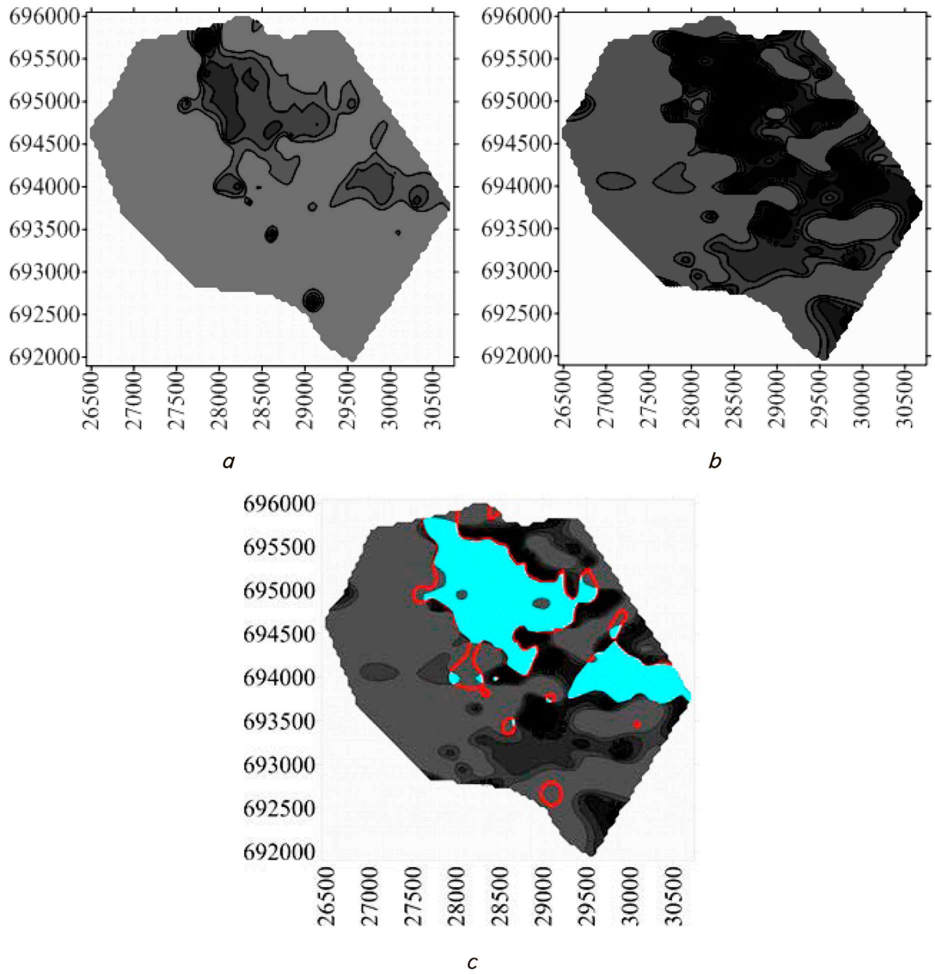


Fig. 7. Example of determining a common area in line with quality indicators in order to calculate the volume of kaolin of the grade “KES-35” for the production of electrothermal silumin and ultramarine with regard to an anisotropy coefficient: *a* — TiO_2 content; *b* —Fe_2O_3 content; *c* — result of plane overlap

5. Results of examining geospatial variability of quality parameters of deposits of primary kaolins

Determining a statistical dependence, in particular the strength of correlation links between the data on quality indicators is important and has practical value in predicting quality indicators in the deposit. By having established a relationship between two indicators, one can approximate it using dependence functions, and, subsequently, when one knows the value of one indicator, it is possible, with a certain probability, to predict the value of another quality indicator.

In the present study, we have analyzed statistical relations between quality indicators of the samples selected from wells of the Zhezhelivsky deposit of kaolins. Dependence between quality indicators was determined using a regression analysis.

Results of a very high correlation between quality indicators are shown in Fig. 8 (correlation pair yellowness – whiteness), Fig. 9 (correlation pair Fe_2O_3 – whiteness), Fig. 10 (correlation pair Al_2O_3 – whiteness), Fig. 11 (correlation pair Al_2O_3 – SiO_2).

In the course of regression analysis of the correlation pairs, it was discovered that there are noticeable, tight and very close links between a significant number of quality indicators of Zhezhelivsky deposit of kaolins. In particular, a noticeable link manifests itself in the following correlation pairs:

– CO_2 and Al_2O_3 (r=0.69);
– CO_2 and SiO_2 (r=–0.66);
– Al_2O_3 and P_2O_5 (r=0.53);
– SiO_2 and P_2O_5 (r=–0.58);
– MgO and Fe_2O_3 (r=0.66);
– MgO and yellowness (r=0.51).

Close link is observed in correlation pairs:

– CO_2 and MgO (r=0.71);
– P_2O_5 and TiO_2 (r=–0.58).

A very close link between the content of:

– Al_2O_3 and SiO_2 (R=–0.98);
– Fe_2O_3 and yellowness (R=0.95);
– Fe_2O_3 and whiteness (R=–0.93);
– yellowness and whiteness (R=–0.97).

In all other correlation pairs, we observed a moderate or weak correlation. The constructed models of correlation pairs allow us using the values of one quality indicator to determine the value of the other quality indicator.

Fig. 8 shows a correlation pair of yellowness and whiteness, Fig. 9 – Fe_2O_3 and whiteness, Fig. 10 – Fe_2O_3 and yellowness, Fig. 11 – Al_2O_3 and SiO_2.

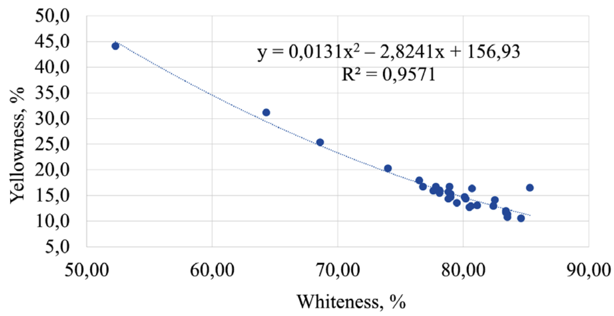


Fig. 8. Regression analysis of the correlation pair yellowness and whiteness

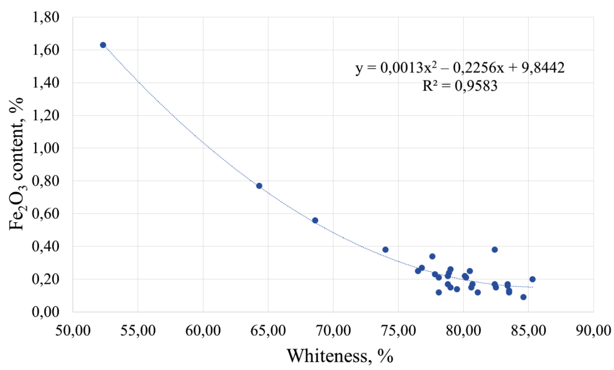


Fig. 9. Regression analysis of the correlation pair Fe_2O_3 and whiteness

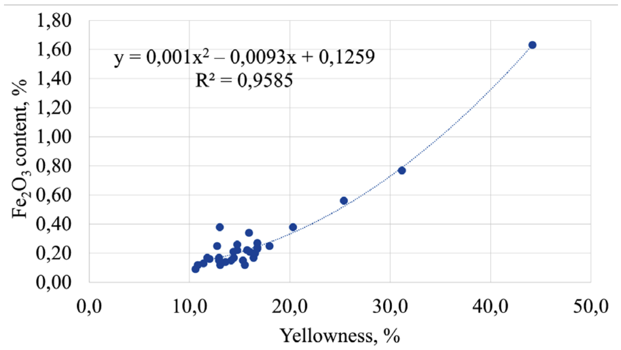


Fig. 10. Regression analysis of the correlation pair Fe_2O_3 and yellowness

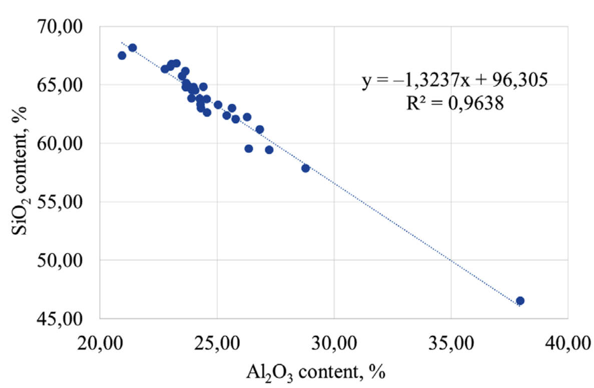


Fig. 11. Regression analysis of the correlation pair Al_2O_3 and SiO_2

Data on a geochemical analysis of the samples selected from 196 wells drilled at the stage of preliminary prospecting of a deposit were supplemented with data from 477 wells of operational prospecting. An analysis of results of constructing variograms for the content of TiO_2, Fe_2O_3 and whiteness, taking into account the degree of prospecting and basic geostatistical indicators, revealed:

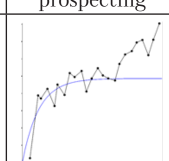
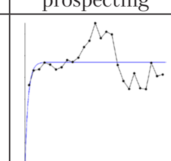
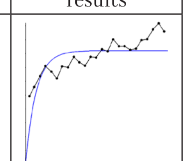
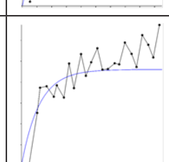
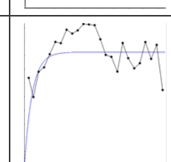
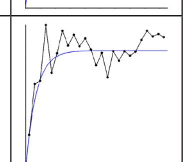
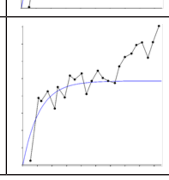
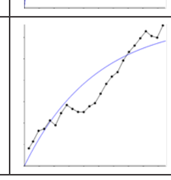
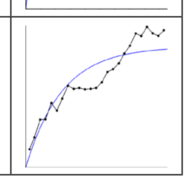
1) During operational prospecting, whiteness at a stretch azimuth of 315° is characterized by a minimal variance (23.5 %) over the range of autocorrelation 43 m. This is explained by the maximal density of explored wells in the given area and by the minimal variability in the values of whiteness. Maximal variance value matches the summary results of operational and preliminary prospecting (41 %), which is 1.7 times larger than that of the operational prospecting, over an autocorrelation range 140 m with a stretch azimuth of 157.5°. Obtained result is possibly explained by a large spatial variability of whiteness over the entire deposit. The results of preliminary prospecting are characterized by an average variance value (30 %) over an autocorrelation range of 435 m at stretch azimuth of 90°, which is explained by a relatively larger impact of uniformity of the network and relatively bigger distance between prospecting wells compared to the summary results.

2) During operational prospecting, Fe_2O_3 at stretch azimuth of 90° is characterized by a minimal variance (0.165 %) over the range of autocorrelation 105 m. Maximal variance value matches the results of preliminary prospecting (0.28 %), which is 1.7 times larger than that of the operational prospecting, over an autocorrelation range of 430 m at stretch azimuth 90°. Simultaneously for the summarized results of preliminary and operational prospecting, they are characterized by the average dispersion value (0.19 %) over an autocorrelation range of 140 m at stretch azimuth 157.5°. Such character of geospatial variability indicates a more uniform change in the content of Fe_2O_3 over the deposit and is accompanied by a rise in the dispersion with a decrease in the number of sampling locations.

Results of the construction of variograms for the content of TiO_2, Fe_2O_3 and whiteness, taking into account the degree of prospecting, are given in Table 9.

Table 9

Results of the construction of variograms, taking into account the degree of prospecting

Quality indicator	Preliminary prospecting	Operational prospecting	Summarized results
Whiteness content			
Fe_2O_3 content			
TiO_2 content			

3) With summarized results of operational and preliminary prospecting, TiO_2 at stretch azimuth 337.5° is

characterized by a minimal variance (0.104 %) over the range of autocorrelation 490 m. Maximal variance value matches the results of preliminary prospecting (0.157 %) over the range of autocorrelation 385 m at stretch azimuth 22.5°. At the same time, the operational prospecting is characterized by the average dispersion value (0.135 %) over an autocorrelation range of 950 m at stretch azimuth 337.5°. It is obvious that there exists an inversely proportional relationship between the amount of data and the value of the variance.

Parameters of the constructed variograms according to the degree of prospecting, and basic geostatistical indicators, are given in Table 10.

Upon outlining the grade areas of the deposit, the issue arises of calculating the reserves of primary kaolins using the above-proposed procedure on the example of Velyko-Gadominetsky deposit. Employing the given procedure, we calculated reserves for all branches of industry where technical requirements imply the use of kaolin to manufacture goods. Results of the performed calculations of the volumes are given in Table 11 [31]. An analysis of the results obtained indicates an insignificant relative mean-weighted error in determining the volumes, which ranges from 0.001 % to 1.067 %.

Upon defining certain grade areas and calculating the volumes of raw materials, there arises an important task on the estimation of error in determining the volumes of the work performed at a mining enterprise. We propose to evaluate the accuracy of determining the volumes of a mineral in the deposit in the following way.

Table 10

Parameters of the constructed variograms according to the degree of prospecting

Indicator	Preliminary prospecting 1971–1977			Operational prospecting			Summarized results		
	TiO_2	Fe_2O_3	whiteness	TiO_2	Fe_2O_3	whiteness	TiO_2	Fe_2O_3	whiteness
Anisotropy coefficient	1.4	1.6	1.5	1.4	1.4	1.13	1.69	1.40	1.65
Azimuth of the maximal value of the degree of correlation of indicators (Angle)	22.5	90	90	337.5	90	315	337.5	0	157.5
Autocorrelation range (Range)	385	430	435	950	105	43	490	140	140
Variance (Sill)	0.157	0.28	30	0.135	0.165	23.5	0.104	0.19	41

Table 11

Determining the amount of kaolin deposit in the Velyko-Gadominetsky field by industries and grades

Industry sector	Grade	Method to determine the volume				Relative mean-weighted error in determining the volume, %
		Trapezoids, m^3	Simpson, m^3	Simpson «3/8», m^3	Mean, m^3	
For the production of electrothermal silumin and ultramarine	KES-37	26599	26300	26471	26456	0.976
	KES-36	2538212	2535277	2538104	2537198	0.215
	KES-35	28785744	28789535	28786357	28787211	0.633
	KUM	34082461	34083520	34084697	34083559	0.064
For chemical industry	KAH-1	31734039	31731295	31731786	31732374	0.021
	KAH-2	67059370	67063118	67054874	67059121	0.018
For ceramic products	KF-1, KFH-1	22535	22631	22452	22540	0.691
	KF-2, KFH-2	95184	95477	95082	95248	1.067
	KF-3, KFH-3	28785744	28789535	28786357	28787211	0.022
	KFP	48582073	48591873	48588611	48587517	0.036
	KS-1	81756987	81742597	81749425	81749670	0.024
	KE-1	3446198	3443723	3445086	3445002	0.136
	KE-2	30881737	30873911	30881161	30878937	0.042
	KE-3	31734039	31731295	31731786	31732374	0.021
For rubber and plastic products, artificial leathers and fabrics	KRt	34277366	34294323	34288499	34286730	0.076
	KRtShP	87582951	87593169	87579409	87585174	0.022
	KR	160490956	160491660	160491704	160491439	0.003
	KKzhT	168067179	168066786	168068007	168067324	0.001

Let us estimate an error in determining the volume using formula (3)

$$V=SH, \tag{3}$$

where

$$S=0,5\sum_{i=1}^{n}x_i\left(y_{i-1}-y_{i+1}\right), \tag{4}$$

$$H=\frac{1}{n}\sum_{i=1}^{n}h_i, \tag{5}$$

$$x_i=x_n+l_{n-i}\cos\alpha_{n-i}\cos\delta_{n-i},$$

$$y_i=y_n+l_{n-i}\sin\alpha_{n-i}\cos\delta_{n-i},$$

$$h_i=h_n+l_{n-i}\sin\delta_{n-i}. \tag{6}$$

After we logarithm formula (3) and, upon differentiating it, we obtain

$$\frac{dV}{V}=\frac{dS}{S}+\frac{dH}{H}.$$

Given that $df\approx\Delta f$, the relative error ε_V when calculating the volume by formula (3) can be estimated according to the following relation

$$\varepsilon_V=\varepsilon_S+\varepsilon_H,$$

$$\varepsilon_V=\frac{\Delta V}{V}=\frac{\Delta S}{S}+\frac{\Delta H}{H}. \tag{7}$$

We shall consider evaluation of relative errors ε_S and ε_H in detail.

Given the above given considerations, one can write

$$2\Delta S=\sum_{i}^{n}\Delta x_i\left(y_{i-1}-y_{i+1}\right)+x_i\Delta\left(y_{i-1}-y_{i+1}\right),$$

$$\Delta H=\frac{1}{n}\sum_{i=1}^{n}\Delta h_i.$$

Employing the principle of equal effects, let us assume $\Delta x_i=\overline{\Delta x}$, $\Delta y_i=\overline{\Delta y}$, $\Delta h_i=\overline{\Delta h}$ for all $i=1....n$. In this case, in order to evaluate an error in the difference $\Delta\left(y_{i-1}-y_{i+1}\right)$, we shall assume the most unfavorable variant when signs Δy_{i-1} and Δy_{i+1} have different signs. Then $\Delta\left(y_{i-1}-y_{i+1}\right)=2\overline{\Delta y}$. We shall receive as a result

$$2\Delta S=\overline{\Delta x}\sum_{i=1}^{n}\left(y_{i-1}-y_{i+1}\right)+2\overline{\Delta y}\sum_{i=1}^{n}x_i,\quad \Delta H=\overline{\Delta h}. \tag{8}$$

Let us estimate $\overline{\Delta x}$ and $\overline{\Delta h}$, using formulas (6).

Evaluation Δx_i. By means of differentiation, it is easy to confirm that

$$\begin{aligned}&\Delta x_i=\cos\alpha_{n-i}\cos\delta_{n-i}\Delta l_{n-i}-\\&-l_{n-i}\sin\alpha_{n-i}\cos\delta_{n-i}\Delta\alpha_{n-i}-l_{n-i}\cos\alpha_{n-i}\sin\delta_{n-i}\Delta\delta_{n-i}=\\&=\left(\Delta l_{n-i}\cos\delta_{n-i}-l_{n-i}\Delta\delta_{n-i}\sin\delta_{n-i}\right)\cos\alpha_{n-i}-\\&-l_{n-i}\Delta\alpha_{n-i}\cos\delta_{n-i}\sin\alpha_{n-i}.\end{aligned}$$

As is known, expression $a\sin t+b\cos t$ takes a maximal value, which is equal to the magnitude $\sqrt{a^2+b^2}$. Then, in the most unfavorable case, error Δx_i is not larger than

$$\Delta x_i=\sqrt{\left(\Delta l_{n-i}\cos\delta_{n-i}-l_{n-i}\Delta\delta_{n-i}\sin\delta_{n-i}\right)^2+\left(l_{n-i}\Delta\alpha_{n-i}\cos\delta_{n-i}\right)^2}.$$

Moreover, the radicand will be estimated as follows. We shall record it in the form

$$\begin{aligned}&\left(\Delta l^2_{n-i}+l^2_{n-i}\Delta\alpha^2_{n-i}\right)\cos^2\delta_{n-i}-\\&-2l_{n-i}\Delta l_{n-i}\Delta\delta_{n-i}\cos\delta_{n-i}\sin\delta_{n-i}+l^2_{n-i}\Delta\alpha^2_{n-i}\sin^2\delta_{n-i}=\\&=A\cos^2\delta_{n-i}+B\cos\delta_{n-i}\sin\delta_{n-i}+C\sin^2\delta_{n-i}=\\&=\left(\frac{A-C}{2}\right)\cos 2\delta_{n-i}+\frac{B}{2}\sin 2\delta_{n-i}+\left(\frac{A+C}{2}\right).\end{aligned}$$

It is obvious that the latter expression takes a maximal value, which is equal to

$$\sqrt{\left(\frac{A-C}{2}\right)^2+\frac{B^2}{4}+\left(\frac{A+C}{2}\right)}.$$

Therefore, the evaluation of error takes the form

$$\overline{\Delta x}=\sqrt{\left(\frac{A-C}{2}\right)^2+\frac{B^2}{4}+\left(\frac{A+C}{2}\right)}, \tag{9}$$

where

$$A=\Delta l^2_{n-i}+l^2_{n-i}\Delta\alpha^2_{n-i},$$

$$B=-2l_{n-i}\Delta l_{n-i}\Delta\delta_{n-i},$$

$$C=l^2_{n-i}\Delta\alpha^2_{n-i}.$$

Evaluation Δy_i. Let us perform similar calculation for Δy_i.

$$\begin{aligned}&\Delta y_i=\sin\alpha_{n-i}\cos\delta_{n-i}\Delta l_{n-i}+\\&+l_{n-i}\cos\alpha_{n-i}\cos\delta_{n-i}\Delta\alpha_{n-i}-l_{n-i}\sin\alpha_{n-i}\sin\delta_{n-i}\Delta\delta_{n-i}=\\&=\left(\Delta l_{n-i}\cos\delta_{n-i}-l_{n-i}\Delta\delta_{n-i}\sin\delta_{n-i}\right)\sin\alpha_{n-i}-\\&-l_{n-i}\Delta\alpha_{n-i}\cos\delta_{n-i}\cos\alpha_{n-i}.\end{aligned}$$

Then, in the most unfavorable case, error Δy_i is not larger than

$$\Delta y_i=\sqrt{\left(\Delta l_{n-i}\cos\delta_{n-i}-l_{n-i}\Delta\delta_{n-i}\sin\delta_{n-i}\right)^2+\left(l_{n-i}\Delta\alpha_{n-i}\cos\delta_{n-i}\right)^2}.$$

Finally, the estimation of error Δy_i takes the form similar to (7), in particular,

$$\overline{\Delta y}=\sqrt{\left(\frac{A-C}{2}\right)^2+\frac{B^2}{4}+\left(\frac{A+C}{2}\right)}, \tag{10}$$

where

$$A=\Delta l^2_{n-i}+l^2_{n-i}\Delta\alpha^2_{n-i},$$

$$B=-2l_{n-i}\Delta l_{n-i}\Delta\delta_{n-i},$$

$$C=l^2_{n-i}\Delta\alpha^2_{n-i}.$$

Evaluation Δh_i. We shall perform calculation for Δh_i. Since

$$\Delta h_i = \Delta l_{n-i} \sin\delta_{n-i} + l_{n-i} \cos\delta_{n-i} \Delta\delta_{n-i},$$

then the maximal value of Δh_i does not exceed

$$\sqrt{(\Delta l_{n-i})^2 + (l^2{}_{n-i}\Delta\delta_{n-i})^2}.$$

That is why we receive that error Δh_i is determined by relation

$$\overline{\Delta h} = \sqrt{(\Delta l_{n-i})^2 + (l^2{}_{n-i}\Delta\delta_{n-i})^2}. \quad (11)$$

Therefore, in order to assess the relative error of determining the volume of ε_V, it is required that formulas (9)–(11) are substituted in formula (8), and then in formula (7).

6. Discussion of results of examining the effectiveness of procedure for the geometrization of deposits of primary kaolins

In the present study, we devised a procedure for the geometrization of deposits of kaolin based on an integrated consideration of quality indicators. This methodology provides a comprehensive approach to modeling the spatial distribution of the values of quality indicators based on their variability. As a result of the performed correlation analysis, we established the main types of relationships between indicators of quality that are described by first and second power polynomials. The main quality indicator of kaolin raw material is whiteness. It defines the grade of kaolin. In general, the deposits of this type are characterized by the fact that it is the content of coloring oxides (Fe_2O_3, TiO_2) that affects the whiteness of the raw material. However, as studies have shown, under geological conditions of Velyko-Gadominetsky field, the content of TiO_2 has no impact on the whitenesss and other indicators of quality. The inverse correlation is observed only between P_2O_5 and TiO_2 (r=–0.58), which has no practical value. This is explained by the low content of TiO_2 over the entire deposit. The dominant coloring oxide is Fe_2O_3, which actually defines the degree of whiteness of kaolins in the given deposit. The value of coefficient of correlation between Fe_2O_3 and whiteness is 0.96.

For the purpose of operational determining the whiteness of a large number of kaolin samples, in the course of present study we devised a procedure for determining the whiteness of primary kaolins using a scanned image of the sample, which formed the basis for creating an algorithm of the software "Whiteness". The implementation of this methodology allowed us to significantly improve performance efficiency in determining the whiteness of kaolins, which is confirmed by the above-described results. However, the issue that remains unsolved is the selection and preparation of the samples to be tested. This stage remains labor-intensive and takes much time. That is why we are considering the prospect of using a portable X-Ray analyser to determine chemical composition of kaolins directly in an excavator bucket, which will make it possible to develop a rapid method for determining basic parameters of the quality of kaolin.

A procedure for modeling the deposits of kaolin raw materials, developed in the present study, enables to improve accuracy in forecasting quality parameters. The result of the implementation of this methodology is the mining-geometrical models of the processes of exploration of a deposit. The application of the given models opens up a possibility to divide a deposit into technological areas with a different quality of raw material and to perform a value-price structuring of reserves. In addition, based on the obtained results, we plan to apply mathematical modeling to control the process of averaging the quality of kaolins in a technological flow.

In the future, this collective of authors plan to construct three-dimensional models of a field by quality indicators with the purpose of the optimization of design solutions when exploring a given deposit. After all, the models we received above allow us you to carry out calendar planning of mining operations at separate horizons.

An analysis of the outlined grade areas revealed that kaolin of the best quality is located mainly in the northern part of the deposit where the mining operations are actually concentrated. High quality of raw material in this area can be explained by active processes of physical and chemical weathering. After all, here is the largest capacity of the kaolin layer. Probably, this territory used to be the mouth of a river, where intense redeposition and disintegration of the granite material, ground by glaciers, took place (in particular, feldspars). In this case, chemical weathering occured in two stages. Initially, as a result of hydrolysis, feldspars passed into clay minerals of the hydromica type, and next, as a result of deep decay, potassium was carried away completely and kaolins formed instead.

Generalization of research results makes it possible to improve the efficiency of quality control in the implementation of certain technological processes of extraction of primary kaolins, based on the improved reliability of modeling a geospatial variability of quality indicators.

7. Conclusions

1. We devised a procedure for highly productive determining of whiteness based on using a flatbed scanner with subsequent processing of color pixel coordinates, which combined high performance, affordable price and reasonable accuracy. The main types of correlation links were established between quality indicators of kaolins for Zhezhelivsky and Veliyko-Gadominetsky deposit: a close relationship between the content of Al_2O_3 and SiO_2 (R=–0.98), Fe_2O_3 and yellowness (R=0.95), Fe_2O_3 and whiteness (R=–0.93), yellowness and whitenesss (R=–0.97). In all other correlation pairs we observed a moderate or weak correlation. The constructed models of correlation pairs enable the development of integral quality indicators of a deposit, which will make it possible to simplify the process of building a model of geospatial variability of quality indicators and to improve effectiveness of quality control at separate technological areas of a deposit.

2. We improved efficiency of mathematical modeling of geospatial variability of quality indicators to control technological processes of extraction and processing of primary kaolins based on determining the optimal models of variograms for various areas of research using a developed plane criterion. We established directions that are characterized by maximal values of a correlation degree: for indicator of Fe_2O_3 and whiteness – azimuth of 90°, the content of TiO_2 – 22.5°. In the course of a variogram analysis we also established the values of anisotropy indicators, which for Fe_2O_3 is 1.6, for TiO – 1.4 and for whitenesss 1.5 over the ranges of autocorrelation of data, respectively, 430 m, 385 m, and 435 m.

3. In order to improve effectiveness when planning technological processes of exploration of deposits, we devised a procedure for geostatistical modeling of geospatial variability of quality indicators, which is based on the use of variograms whose type is determined based on a plane criterion, and takes into account anisotropy of indicators. The implementation of the developed procedures to determine the volume of Velyko Gadominetsky deposit of primary kaolins with respect to the grade differentiation using the proposed methodology is characterized by minimal values of relative mean-weighted error in determining the total amount of grade, which ranges from 0.001 % to 1.067 %.

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