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APPLICATION OF GIS ANALYSIS FOR ENGINEERING AND GEOLOGICAL ASSESSMENT OF KIMBERLITE DEPOSITS

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ЗАСТОСУВАННЯ ГІС АНАЛІЗУ ДЛЯ ІНЖЕНЕРНО-ГЕОЛОГІЧНОЇ ОЦІНКИ КІМБЕРЛІТОВИХ РОДОВИЩ

The **purpose** of the research is to develop a methodology for analyzing the geological data of a kimberlite deposit based on the presence of kimberlite indicator minerals to optimize mining operations using geoinformation systems.

Method. Interpolation and approximation methods are used to represent the terrain, with the choice depending on the quantity, density, and uniformity of input data distribution within the study area. Spatial interpolation enables the identification of distribution patterns of the studied parameters using Kriging methods and radial basis functions. Trend surfaces are generated using polynomial regression. For rapid evaluation of large datasets, minimum curvature and triangulation methods with linear interpolation are applied.

Findings. The result of the study is an analysis of the spatial location of the deposit, mapping of mineral deposit zones with the identification of change patterns, and the construction of a digital three-dimensional model of the deposit with spatial analysis of the distribution of numerical indicators of kimberlite indicator minerals.

Originality. This article proposes, for the first time, a methodology for optimizing mining operations by creating a 3D geoinformation model that displays information on the location of geological zones within the studied deposit and the prevailing kimberlite indicator minerals in these zones. This methodology allows for increased exploration accuracy, optimized mineral extraction, and reduced environmental risks.

Practical implementation. The practical significance lies in optimizing the planning and execution of mining operations based on GIS analysis of kimberlite deposits. This allows for more accurate prediction of indicator mineral distribution, identification of profitable areas, reduction of costs, and environmental impact. The application of GIS facilitates decision-making at all stages of the mining process.

Keywords: *geological surveys, geo-information systems, kimberlite pipe, kimberlites, three-dimensional modeling, borehole, engineering-geological section, indicator minerals in kimberlite deposits, geodetic monitoring, interpolation.*

Introduction. Geoinformation systems (GIS) play a crucial role in the mining industry, assisting in various tasks at all stages of deposit development, from prospecting to land reclamation. The described method for analyzing geological studies of a deposit to assess the distribution of kimberlite indicator minerals is a valuable tool for determining effective directions for mining operations.

One of the key aspects of this approach is the use of GIS to analyze spatial variations in mineral deposits. This includes mapping the distribution of these minerals and creating a digital model of the deposit, incorporating spatial analysis of numerical indicators representing the presence of kimberlite indicator minerals (KIM).

A ternary diagram can be used to analyze the content of kimberlite indicator minerals, displaying the relative abundance of different minerals in the samples. Additionally, 3D modeling in the Surfer software enables the visualization of mineral concentrations in boreholes, allowing for an accurate assessment of their spatial distribution.

The resulting three-dimensional model of borehole locations, indicating the quantitative content of minerals, serves as an essential tool for analyzing and planning mining operations. It helps to orient mining activities toward specific valuable minerals or to assess mineral quality.

Overall, the integration of geoinformation systems in the mining industry optimizes production processes, ensuring efficient and environmentally sustainable operations. GIS enables the combination of spatial data into a visual format, facilitating informed decision-making at all stages of field development.

The given review demonstrates that for a mineral deposit, not only qualitative data is important, but also quantitative data that characterizes the presence of specific minerals in different zones of the deposit. This data determines the sequence and technology of extraction. Analyzing the geographic structure of quantitative data is a key aspect of location analysis. Such analysis allows for the comparison of objects based on their quantitative characteristics, the identification of areas that meet specified criteria, and the detection of spatial relationships between quantitative indicators.

The use of graphical methods, such as a two-dimensional ternary diagram, is not particularly convenient in practice and does not provide comprehensive information for displaying the relative abundance of different minerals in samples. Moreover, it lacks the capability for rapid and effective analysis of geological research results.

The purpose of this study is to improve methods for analyzing geological studies of a deposit based on the presence of kimberlite indicator minerals. The goal is to determine effective directions for mining operations under the conditions of the Mothae kimberlite deposit (South Africa), where the diverse mineral composition of diamond-bearing kimberlites is of fundamental importance.

Description of the object of research. The Mothae kimberlite is located in the highlands of Lesotho at an altitude of 2,900 meters above sea level, in the southern part of the Kaapvaal Craton. Geological studies have established that the Kaapvaal Craton hosts numerous significant diamond-bearing kimberlites of various ages [1, 2].

As a result of large-scale sampling of the Mothae kimberlite, conducted between 2008 and 2012, a total of 603,819 tons of material were processed, yielding 23,446 carats of diamonds, with an average stone size of 0.45 carats [3].

Studies have also found that kimberlites with a higher diamond concentration are typically located in geological regions that have remained tectonically stable since the Archean [4]. The Archean basement in Lesotho is entirely covered by Paleozoic-

Mesozoic rock layers, with a total thickness of approximately 4,000 meters. These layers consist primarily of shales, sandstones, mudstones, and limestones, which were deposited over a period of about 100 million years, from the Late Carboniferous to the Early Jurassic. Overlying these sedimentary layers are the basalts of the Drakensberg Group, which erupted over a relatively short period during the Jurassic. These basalts form a homogeneous sequence of complex basaltic lava flows, with thicknesses reaching up to 1,400 meters across the craton [3, 5, 6].

This article analyzes data from a site located in the highlands of Lesotho, which includes a Production Area covering 20.52 km² and a Protection Area spanning 26.33 km². The coordinates of the site boundaries are provided in table 1 [3].

Table 1

Coordinates of the points of the Production Area and the Protection Area in the WGS84 coordinate system

Mining Area	Points	Latitude, DD	Longitude, DD	Mining Area	Points	Latitude, DD	Longitude, DD
Production Area	1	-28.948610	28.786390	Production Area	8	-28.996670	28.786390
Production Area	2	-28.948610	28.826920	Protection Area	A	-28.938967	28.772256
Production Area	3	-28.957270	28.826920	Protection Area	B	-28.938967	28.849136
Production Area	4	-28.957270	28.833340	Protection Area	C	-28.970833	28.849136
Production Area	5	-28.970830	28.833340	Protection Area	D	-28.970833	28.821667
Production Area	6	-28.970830	28.821670	Protection Area	E	-29.009028	28.821667
Production Area	7	-28.996670	28.821670	Protection Area	F	-29.009028	28.772256

Using the Google Earth Pro and the data from table 1, a map of the Mothae area with the Production and Protection Areas was obtained, which is presented in figure 1.

In the process of conducting geological exploration work with the aim of establishing the capacity of overburden and obtaining representative samples of kimberlite, 73 wells were drilled, 51 of them crossed the kimberlite, the rest of the wells crossed the basalt base or did not reach the base. The obtained samples were used for further petrographic analysis. Information on the parameters of the drill-holes, namely coordinates, azimuth, inclination angle, length, is given in table 2 [3].

The Mothae kimberlite is located within the Production Area and consists of 3 main zones: the main southern pipe-shaped area of 5.05 ha, which in turn is divided into south-western (SW), south-eastern (SE) and south-central (SC) areas, a smaller northern (N) zone and a central kimberlite body connecting the southern and northern zones (figure. 2). The total area is 8.81 ha.

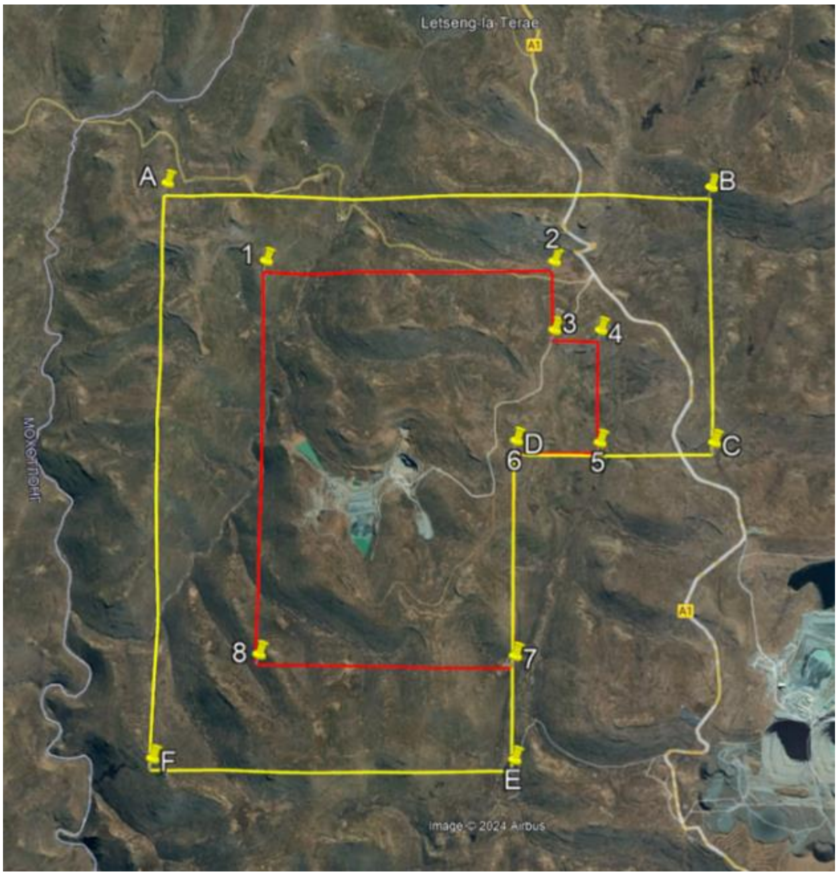

Fig. 1. Map of the Mothae deposit area with the Production Area (red line) and the Protection Area (yellow line) highlighted

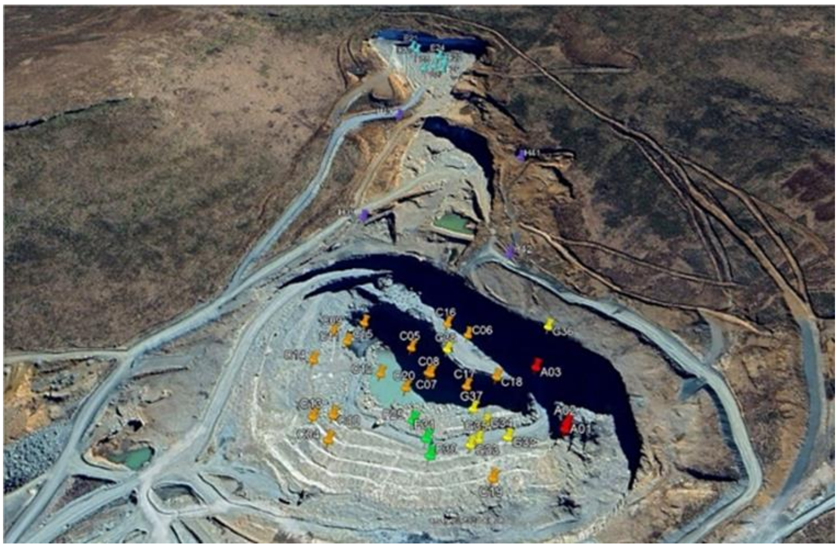

Fig. 2. Research area with mapped drill-holes

Estimated diamond resources of the Mothae kimberlite within these zones as a function of the depth is given in table 3 [3].

Table 2

Information about boreholes

Drill-hole number	X UTM35S	Y UTM35S	Z	Azimuth	Inclination	Length, m
A01	676142	6793674	3011	-	-89	298
A02	676145	6793680	3011	95	-61	74
A03	676125	6793740	3020	90	-70	105
C04	675959	6793675	3003	225	-55	95
C05	676020	6793770	3012	10	-49	221
C06	676069	6793782	3013	75	-60	51
C07	676035	6793742	3014	190	-59	251
C08	676037	6793741	3014	110	-59	272
C09	675951	6793880	3013	345	-70	152
C10	675960	6793699	2992	-	-89	301
C11	675964	6793778	3002	-	-89	301
C12	675995	6793742	2992	-	-88	200
C13	675944	6793698	2992	250	-58	123
C14	675938	6793758	3002	270	-59	111
C15	675978	6793800	3001	350	-59	114
C16	676051	6793797	3005	20	-65	93
C17	676067	6793725	2997	55	-65	146
C18	676092	6793734	2998	-	-89	300
C19	676085	6793634	3003	35	-63	288
C20	676017	6793726	2990	300	-68	351
E21	676007	6794216	3081	293	-60	130
E22	676047	6794189	3075	68	-65	105
E23	676034	6794180	3075	0	-65	164
E24	676040	6794198	3073	-	-89	191
E25	676022	6794176	3073	245	-71	120
E26	676044	6794174	3073	120	-74	113
E27	676013	6794210	3076	345	-64	120
F29	676024	6793691	3001	290	-55	251
F30	676038	6793657	3002	180	-50	92
F31	676035	6793673	2994	210	-59	177
G32	676098	6793671	3004	135	-60	152
G33	676069	6793666	2994	-	-89	302
G34	676081	6793686	2994	90	-53	200
G35	676075	6793671	2993	170	-60	140
G36	676139	6793784	3020	207	-55	150
G37	676072	6793701	2998	-	-89	301
G38	676051	6793767	2999	-	-88	102
H39	675966	6793933	3031	90	-60	261
H40	675995	6794093	3056	90	-59	153
H41	676129	6794019	3046	270	-54	210
H42	676110	6793879	3025	270	-56	222

The data shows that the highest concentration of diamonds was found in the southern central zone of the area under consideration (4.4-4.6 ct/100t). The largest amount of diamonds was mined in the south-western zone (0.53 Mct).

Table 3

Mothae diamond resource estimate

Resource zone	Volume, Mm^3	Bulk Density, g/cm^3	Tons, Mt	Concentration, ct/100t	Total Resource, Mct
SW-WX[a]	0.37	2.02	0.75	2.6	0.02
SW-50	0.43	2.52	1.08	2.5	0.03
SW-300	7.39	2.62	19.35	2.5	0.48
SC-WX[a]	0.11	2.11	0.23	4.6	0.01
SC-50	0.14	2.47	0.33	4.4	0.01
SC-300	1.52	2.55	3.88	4.4	0.17
SE-WX[a]	0.14	2.04	0.29	2.8	0.01
SE-50	0.24	2.39	0.56	2.6	0.01
SE-300	2.39	2.48	5.94	2.6	0.15
N-WX[a]	0.29	2.07	0.59	2.5	0.01
N-300	2.39	2.49	5.96	2.4	0.14

[a] WX is weathered material

Methods. Real objects considered in geoinformation differ in spatial, temporal and thematic characteristics [7–9]. Spatial characteristics determine the position of the object in a predetermined coordinate system. In the Google Earth Pro software, the description of a point or linear object is carried out by specifying the X, Y coordinates. To display the surface, you need to add height marks to the coordinates of planar objects. This is done using mathematical algorithms (interpolation and approximation) [10]. We used GPS Visualizer software. The construction of a digital model of the relief requires a certain form of representation of the initial data (a set of X, Y, Z point coordinates) and a method of their structural description, which allows restoring the surface by interpolation or approximation of the initial data. Data files were created and, using the Kriging interpolation algorithm, grid maps were created as GRID files in the Surfer program. As a result, a contour map of the production area was constructed, which is presented in figure 3.

The geological section of the area under consideration is presented in figure 4. In the geological structure, there are several groups of rocks that were formed over millions of years, namely Dwyka Gr. (shales, siltstones), Ecca Gr. (sandstones, shales), Beaufort Gr. (sandstones, red argillites, shales), Stormberg Gr. (limestones, mudstones, sandstones), Drakensberg Gr. (basalts). The three-dimensional model of the surface and the geological section is created due to the three-dimensional shadow representation of the grid file with the addition of elevation marks of the surface and layers of the section (Z coordinates) of the corresponding grid node [2, 3].

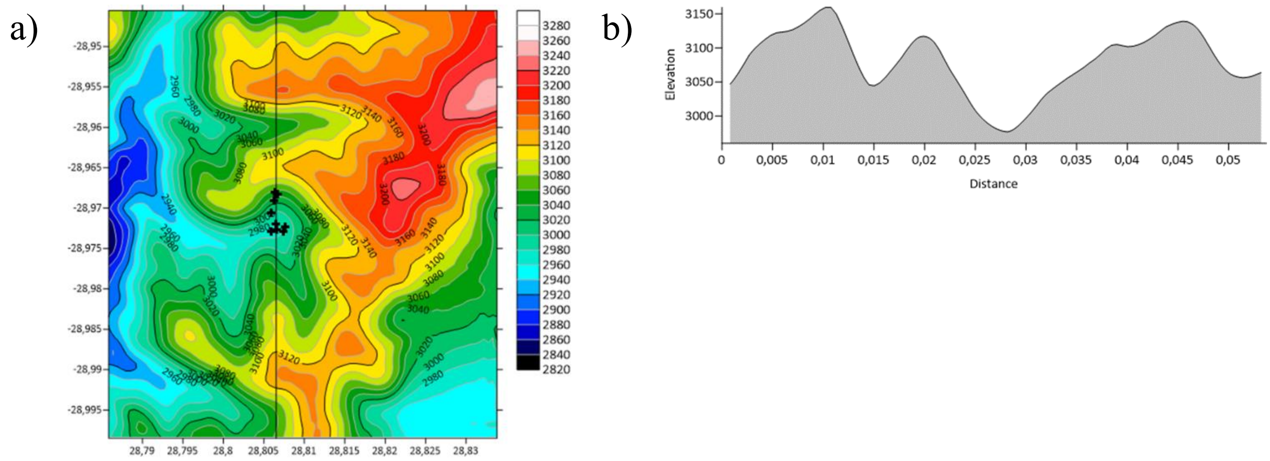

Fig. 3. Contour map of the production area (a) with a section by well location (b)

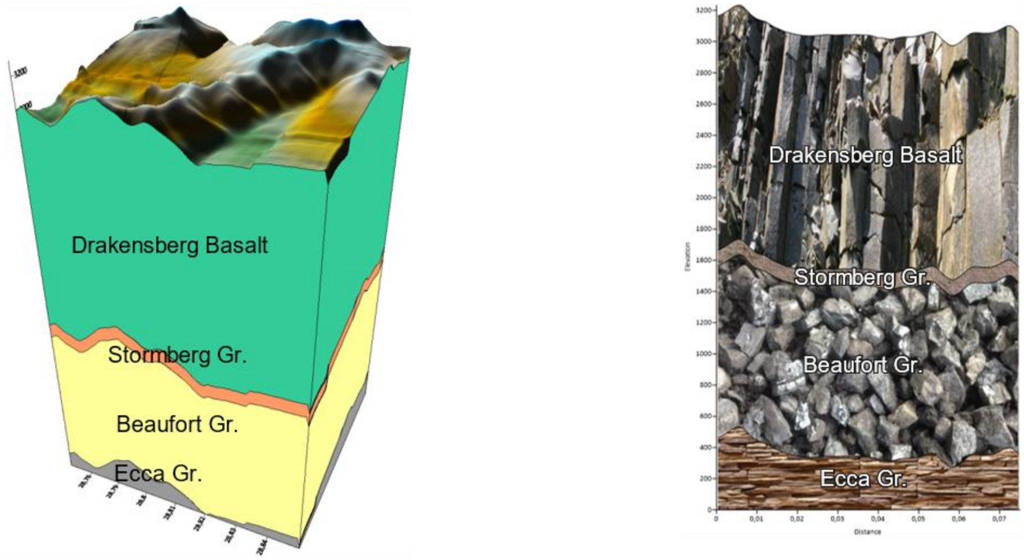

Fig. 4. 3D-view of the production area with a geological section

Using the Drillhole map tool, it is possible to visualize the location of drill-holes, taking into account their length, angle of inclination and orientation in space (azimuth). In figures 5 and 6 present spatial models of the location of wells.

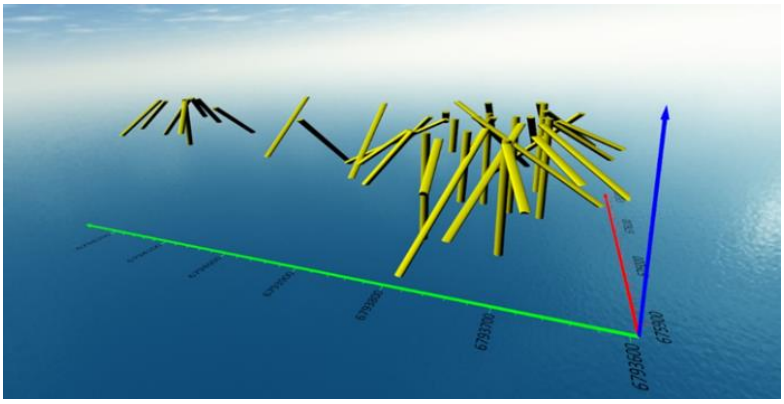

Fig. 5. 3D model of the well trajectory with display of different types of data

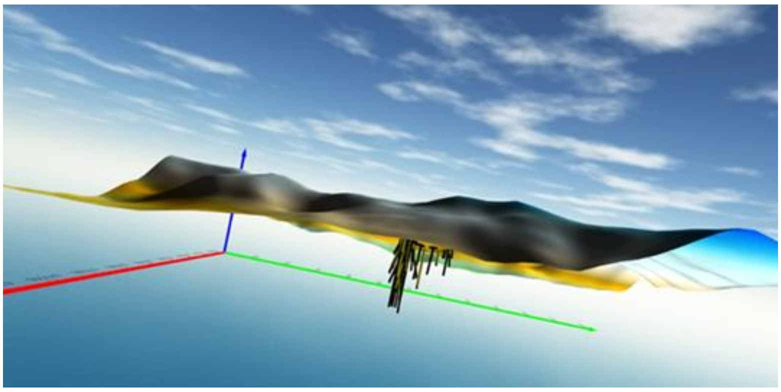

Fig. 6. Visualization of well tracks in conjunction with the relief surface

The result of importing the well parameters into a 2D view showing the location of the wellheads of inclined wells with their projections on the surface and traces of drilling holes relative to the Mothae pipe contour is shown in figure 7a. The color visualization of the topography map in combination with projections on the surface of inclined well tracks is shown in figure 7b. The representation of wells in different colors helps to reflect their belonging to different zones (south-western, south-eastern, south-central, northern zone and central kimberlite body).

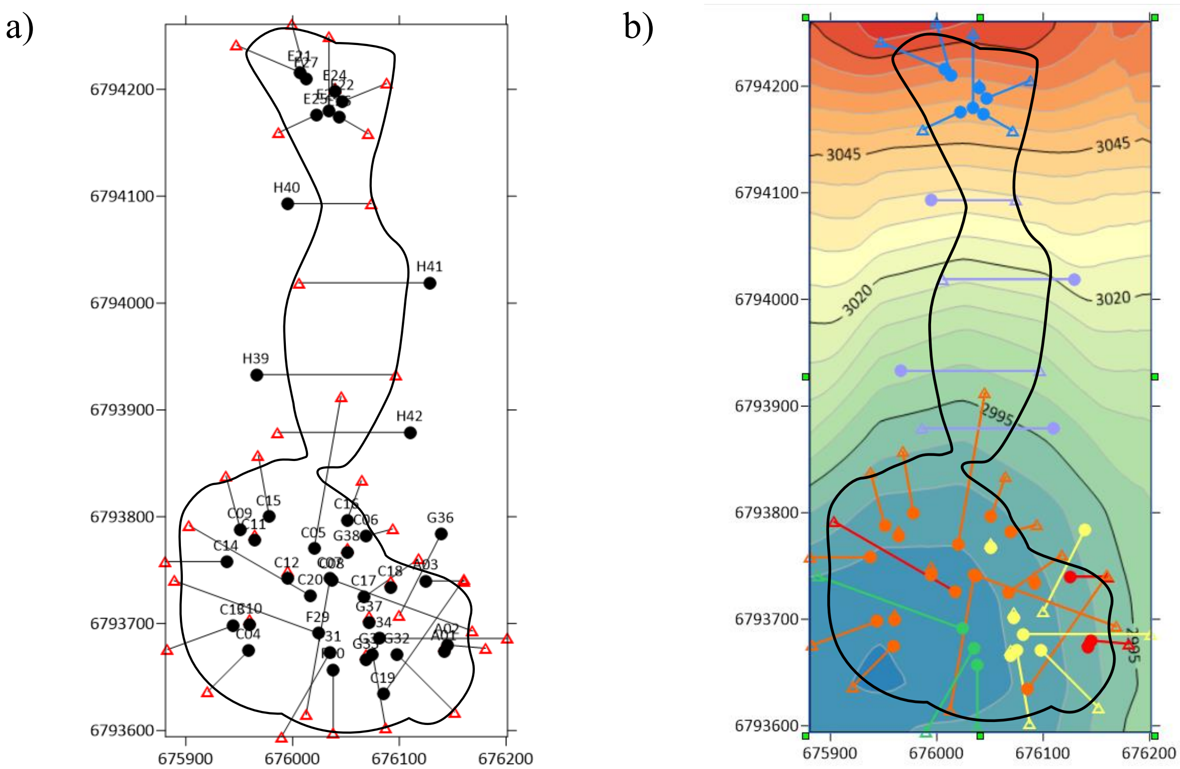

Fig. 7. Plan view of projections of inclined wells with traces of drilling holes relative to the kimberlite tube contour

Results and discussion

1. Estimation of the concentration of kimberlite indicator minerals. As a result of the petrographic analysis of the boreholes presented in table 2, the presence of kimberlite indicator minerals (KIM) in the geological formation was confirmed, suggesting the possible occurrence of diamonds in this area. The most characteristic KIMs in the study area include pyrope and eclogite garnets, chromian diopside, picroilmenite, and olivine [5, 10].

Garnets in kimberlites occur as micro- and macrocrystalline grains, mostly rounded in shape, with sizes reaching up to 7–8 mm. They can exist as individual xenocrysts or be enclosed within xenoliths. Both pyrope and eclogite-type garnets are present at this deposit. Pyrope garnet (PGar) is typically red, but it can also appear pink, brown, or black. It is usually found in kimberlite formations in association with olivine, ilmenite, chromian diopside, and diamonds. Eclogite garnets are green and often occur alongside pyrope. The Cr_2O_3 content in garnets generally ranges between 3% and 8%, allowing them to be used as KIMs. Garnets frequently serve as diamond carriers, potentially retaining diamonds within their crystal structure [11]. Picroilmenite (PIlm) is one of the most significant typomorphic minerals in kimberlite rocks. In kimberlites, it occurs as rounded or angular grains, ranging in size from fractions of a millimeter to several millimeters. The average Cr_2O_3 content in picroilmenite is approximately 2.4%. It is commonly found in kimberlite rocks along with grains of garnet, diopside, olivine, and other KIMs.

Chromian diopside (Chr) is also a crucial indicator mineral in geological research and diamond exploration. It has a dark green or greenish-black color and occurs as individual crystals or crystalline aggregates. The Cr_2O_3 content in chromian diopside can reach up to 2%. Occasionally, it is found as inclusions in diamonds, giving them a greenish hue.

Olivine plays a key role in geological research and diamond exploration due to its relative abundance in kimberlite formations and its strong association with diamonds. It is a well-known kimberlite indicator mineral, typically displaying green or yellow-green coloration. The average size of olivine grains in kimberlites ranges from a few millimeters to several centimeters. Olivine occurs as distinct crystals, crystallizing within the kimberlite magmatic system at various stages of ascent from mantle depths [11].

To delineate the kimberlite body contour and identify internal domains that may represent different geological units or kimberlite types based on the quantitative content of KIMs, five geological zones were established: Southwest (Zone C); South-central (Zones F and G); Southeast (Zone A); North (Zone E); Central kimberlite body (Zone H). Information on the KIM content in individual boreholes is provided in table 4 [3].

On the basis of the presented data on the percentage content of the predominant kimberlite indicator minerals, a triangle graph was constructed showing the relative amount of PGar, PIlm and Chr in the KIM samples (fig. 8).

From the graph obtained, it can be concluded that, depending on the quantitative content of the prevailing KIMs, kimberlites of different geological zones will belong to different types. Thus, for the southwestern geological area (zone C), the predominant KIM is PGar (50–66%). The content of other KIMs: OGar – 21–42%, Chr – 5-16%. The southern center (zone F and G) is characterized by the predominant amount of the mineral PGar 47–58%. Therefore, the kimberlites of the southwest and south center belong to the garnet type. For the southeastern area (zone A) and the area of the central kimberlite body (zone H), the predominant KIM is Chr (51–54% and 80–100%, respectively), the kimberlites of these groups belong to the chromdiopside type. In the northern geological area (zone E), three KIM are present in approximately equal parts, these are mixed-type kimberlites.

Table 4

Content of kimberlite indicator minerals (KIM) by wells

Zone	Drill-hole number	KIM content, %			Zone	Drill-hole number	KIM content, %		
		PGar	PIlm	Chr			PGar	PIlm	Chr
A	A01	38	11	51	E	E21	27	27	46
	A02	39	7	54		E22	36	23	41
	A03	37	12	51		E23	36	24	40
C	C04	66	21	13		E24	36	25	39
	C05	63	21	16		E25	28	34	38
	C06	59	27	14		E26	36	27	37
	C07	56	28	16		E27	38	27	35
	C08	55	30	15	F	F29	47	31	22
	C09	64	25	11		F30	53	26	21
	C10	62	27	11		F31	55	25	20
	C11	65	29	6	G	G32	50	13	37
	C12	62	30	8		G33	51	18	31
	C13	63	35	2		G34	47	22	31
	C14	56	37	7		G35	46	23	31
	C15	54	38	8		G36	58	13	29
	C16	52	39	9		G37	53	23	24
	C17	50	42	8		G38	48	18	34
	C18	57	35	8	H	H39	10	30	60
	C19	61	34	5		H40	10	11	79
	C20	59	32	9		H41	18	2	80

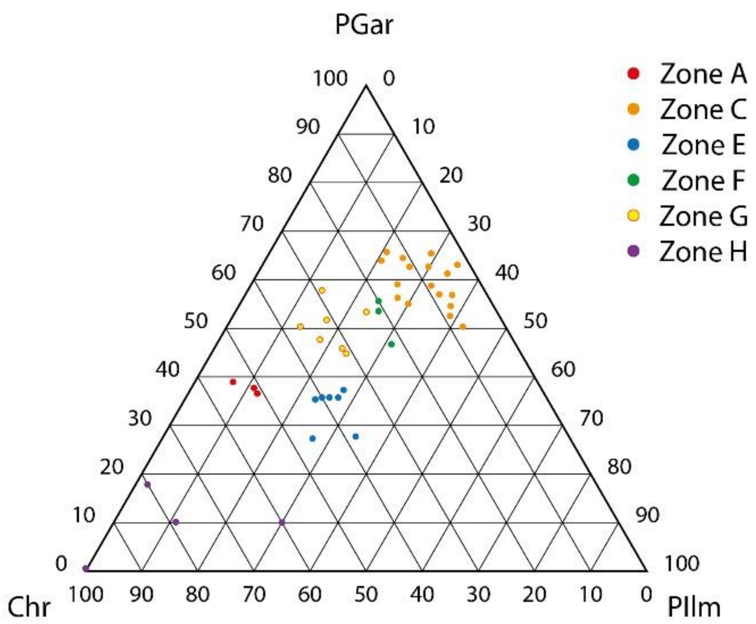

Fig. 8. Graph-triangle of kimberlite indicator minerals

2. Visualization of the concentration of kimberlite indicator minerals. Visualization of KIM concentration can be done using 3D modeling in the Surfer program. The content of each of the considered KIMs in the well is highlighted in a separate color. A new type of symbol - a sphere - is used to display point vector data of mineral concentrations in a well. The number of spheres of a certain color corresponds to the percentage content of the corresponding mineral in a specific well. So, the predominant color can be used to determine the predominant KIM. According to the data in tables 2 and 4, a three-dimensional model of the location of the wells was created, considering the direction, length, slope, wellhead mark and indicating the quantitative content of KIM (fig. 9).

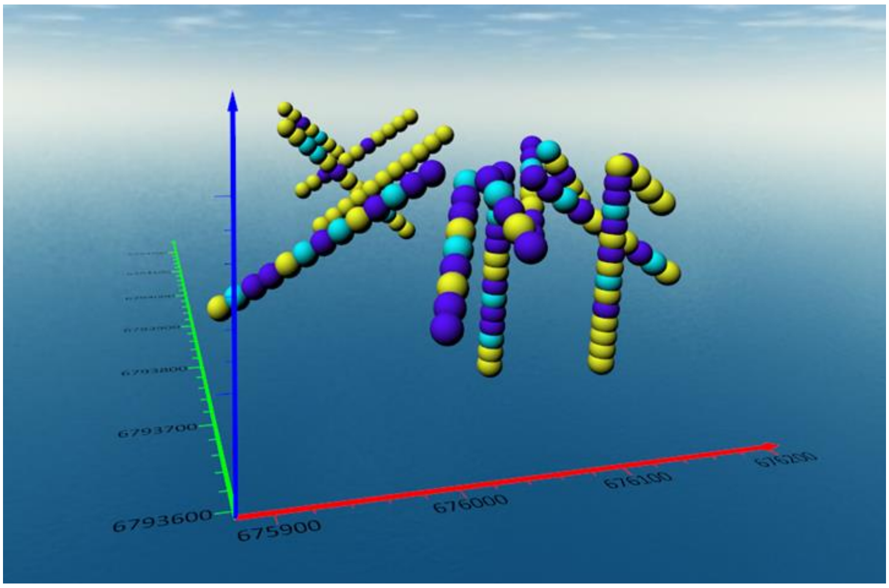

Fig. 9. 3D display of interval well data on the predominance of certain indicator minerals

The resulting three-dimensional model is a combination of information on the location of geological zones within the study area (see fig. 7b) and the prevailing KIM in these zones (see fig. 8), i.e., one can see the zone and the mineral-indicator prevailing in this zone in one figure.

From the obtained model, it can be concluded that each kimberlite domain consists mainly of one type of kimberlite. The Southeastern, Southcentral, and Southwestern domains make up the main fill of the Southern Lobe pipe. Thus, for the southwestern geological area and the southern center, the dominant KIM is pyrope garnet (blue color). Therefore, the kimberlites of the southwest and south center belong to the garnet type. For the southeastern area, the predominant KIM is chromdiopside (yellow color), and the kimberlites of this group belong to the chromdiopside type. The area of the central kimberlite body consists mainly of kimberlite of the chromdiopside type, as chromdiopside (yellow color) predominates. The Northern Domain constitutes the main infill of the Northern Lobe pipe, kimberlite indicator minerals are present in this zone in approximately equal parts, they are mixed-type kimberlites.

Conclusions. The use of geographic information systems (GIS) in the mining industry is a key factor in optimizing production processes, ensuring efficient and environmentally sustainable operations. Three-dimensional modeling of geological sections and surfaces using Surfer software provides a visual representation of the geological structure of the studied area, enhancing the understanding of geological conditions and improving the forecasting of mineral resource locations.

Analyzing geological surveys of deposits with GIS is a valuable tool for identifying optimal mining areas, from early-stage exploration to land reclamation. The application of GIS for analyzing spatial variations in mineral occurrence – including mapping their distribution and developing digital deposit models – enables the precise identification of locations with high potential for the extraction of kimberlite indicator minerals.

The generated three-dimensional model of borehole locations, displaying the quantitative mineral content, serves as a crucial tool for mining analysis and planning. It facilitates the targeted extraction of specific minerals and enhances the efficient utilization of deposits.

The analysis of diamond quantity and concentration in different sections of the study area reveals a heterogeneous distribution of valuable minerals within the Mothae kimberlite, necessitating more meticulous planning of mining operations. The proposed method for analyzing geological studies of the deposit enables the determination of optimal mining strategies, whether focused on a specific mineral or a particular mineral quality.

The integration of GIS tools for analyzing and visualizing data on borehole locations and diamond concentrations across the deposit is essential for the effective management of mining operations.

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АНОТАЦІЯ

Метою дослідження є розробка методики аналізу геологічних даних кімберлітового родовища за наявністю мінералів-індикаторів кімберліту для оптимізації гірничодобувних робіт із застосуванням геоінформаційних систем.

Методика. Для відображення рельєфу застосовуються методи інтерполяції та апроксимації, вибір яких залежить від кількості, щільності та рівномірності розподілу вихідних даних у межах досліджуваної території. Просторова інтерполяція дозволяє виявити закономірності розподілу досліджуваних параметрів за допомогою методів Крігінгу та радіальних базисних функцій. Трендові поверхні створюються за допомогою поліноміальної регресії. Для швидкої оцінки великих масивів даних застосовуються методи мінімальної кривизни та тріангуляції з лінійною інтерполяцією.

Результатом дослідження є аналіз просторового розташування родовища, картографування зон залягання корисних копалин із виявленням закономірностей змін, побудова цифрової тривимірної моделі родовища з просторовим аналізом розподілу числових показників мінералів-індикаторів кімберліту.

Наукова новизна. У статті вперше запропоновано методику оптимізації гірничодобувних робіт шляхом створення 3D геоінформаційної моделі, яка відображає інформацію щодо розташування геологічних зон в межах досліджуваного родовища і переважаючих мінералів-індикаторів кімберліту в цих зонах. Ця методика дозволяє підвищити точність розвідки, оптимізувати видобуток корисної копалини та зменшити екологічних ризиків.

Практична значимість полягає в оптимізації планування і виконання гірничодобувних робіт на основі ГІС-аналізу кімберлітових родовищ. Це дозволяє точніше прогнозувати розподіл мінералів-індикаторів, виявляти прибуткові ділянки, знижувати витрати та екологічний вплив. Застосування ГІС полегшує прийняття рішень на всіх етапах гірничодобувного процесу.

Ключові слова: *геологічні вишукування, геоінформаційні системи, кімберлітові трубки, кімберліти, тривимірне моделювання, свердловина, інженерно-геологічний переріз, мінерали-індикатори кімберлітів, геодезичний моніторинг, інтерполяція.*