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INTEGRATION OF GIS AND GEODETIC MONITORING FOR GOLD DEPOSIT MODELING AND MINE PLANNING

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Abstract. This study presents an in-depth geospatial and geodetic analysis of the Tulallar gold deposit using modern 3D modeling techniques. A dataset of 152 exploratory boreholes, totaling 17,705.55 meters in depth, served as the foundation for a detailed three-dimensional model developed in Golden Software Surfer. The research aimed to visualize the spatial distribution of gold-bearing ores and quantify the variability in gold concentrations at different depths and across various geological zones.

Advanced GIS tools, including the Drillhole module and Kriging interpolation method, were applied to accurately depict subsurface mineralization. The analysis revealed pronounced zoning, particularly in the southwestern sector, where gold concentrations reached up to 7.5 g/t, compared to lower values in the central and northern parts of the deposit. The addition of topographic layers, isosurfaces, and contour mapping allowed dynamic interpretation of ore body morphology, zoning, and depth distribution.

The constructed 3D models enabled not only the identification of economically viable mineral zones but also the visualization of their spatial configuration with a high degree of accuracy. Such models allow geologists to assess the relationship between ore concentration and terrain elevation, facilitating more strategic decisions in exploration and mining planning.

This integrated geodetic and GIS-based approach proved to be effective for visualizing the geometry of economically viable mineralized zones. The results confirm that the southern zone holds the highest potential for future exploitation, with implications for more precise resource estimation, optimized mining strategies, and environmentally sustainable planning. The conducted analysis demonstrated that gold concentrations in the southwestern part of the study area significantly exceed those observed in the central and northern zones.

Thus, by varying both elevation and concentration data, it is possible to perform a comprehensive and accurate analysis of the deposit. This approach not only enables the identification of optimal depths for mining, but also provides a rational basis for selecting appropriate extraction technologies. The resulting data form a solid foundation for reliable resource estimation and strategic planning of deposit exploitation.

Keywords: Gold deposit, 3D modeling, GIS technologies, kriging interpolation, borehole data, mineral resource estimation, geodetic monitoring, spatial analysis, surfer software, ore body visualization.

1. Introduction

Accurate assessment and spatial characterization of mineral deposits play a pivotal role in ensuring the sustainable and economically efficient development of mining operations. Conventional geological approaches, such as two-dimensional maps and cross-sections, often fall short when it comes to representing the true complexity of ore body geometry, particularly in structurally diverse and mineralogically variable environments. Modern advancements in geodetic monitoring and Geographic Information System (GIS) technologies, combined with three-dimensional (3D) modeling tools, provide an enhanced framework for visualizing and interpreting subsurface structures with greater precision and reliability.

This study focuses on the Tulallar gold deposit, located in the Gadabay District of western Azerbaijan. Tulallar is a relatively young and actively developing deposit within the Lesser Caucasus metallogenic province, which is known for its rich polymetallic and gold-bearing formations. The region's geological structure is complex, characterized by volcanic-sedimentary sequences, hydrothermal alterations, and significant faulting, which together influence the localization and concentration of gold-bearing quartz veins and ore bodies (Fig.1).

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Figure 1 – Panoramic view of the Tulallar gold deposit open-pit mine located in the Lesser Caucasus region, showcasing terraced excavation levels and surrounding forested landscape

Preliminary exploration at the Tulallar site revealed the presence of epithermal gold mineralization primarily hosted in quartzite formations, with gold content showing high lateral and vertical variability. Over 150 exploratory boreholes were drilled to delineate the ore zones and assess their economic potential. These data provide the foundation for a geodetically accurate and geologically informed 3D model that supports efficient mine planning and resource management.

The aim of this research is to build a high-resolution 3D model that captures the spatial variability of gold concentrations within the deposit. The integration of borehole data, topographical information, and advanced interpolation techniques allows for a more comprehensive understanding of ore distribution and zoning. This modeling effort not only enhances the predictive accuracy of resource estimation but also contributes to the selection of optimal extraction methods and environmentally responsible mining strategies.

2. Methods

Data Collection: Geological exploration results, borehole data (coordinates, elevations, gold concentrations), and topographic measurements were gathered.

Coordinate System: All data were unified using UTM Zone 38 and the Baltic Height System. Spatial referencing was based on the fourth-order national geodetic network [1, 2].

Software and Tools: The Surfer software was used for interpolation, 3D modeling, and visualization, primarily through its “Drillhole” and “3D View” modules. Kriging interpolation was applied to generate accurate digital elevation and concentration surfaces.

In Kriging estimation equation, value of the variable at an unsampled location X_0 is estimated as a weighted linear combination of the known values from surrounding sample points:

$$\hat{Z}(x_0) = \sum_{i=1} \lambda_{ii}$$

where $\hat{Z}(x_0)$ – the estimated value at location x_0, $Z(x_i)$– the measured value at sample location i, λ_i – the kriging weight assigned to sample i, n – the number of neighboring samples used [3].

Visualization: Color and sizing methods were employed to visualize concentration changes along boreholes. Isoline maps and isosurfaces were created for various gold thresholds (2.5, 4.5, and 6.5 g/t).

3. Theoretical and experimental part

The integration of borehole data into Surfer enabled the creation of both two-dimensional contour maps and three-dimensional models [4]. These visualizations illustrated the spatial heterogeneity of gold distribution across central and southern zones:

In the southern zone, gold concentration ranged from 2.5 g/t to 7.5 g/t, with an average of 2.41 g/t. High-grade clusters were primarily located in the southwestern region.

In the central zone, values were lower and more heterogeneous, ranging between 0.7 and 3.5 g/t, with an average of 1.9 g/t.

3D isosurfaces revealed vertical zoning effects: at 1500 m elevation, southwestern parts had peak values, which decreased slightly at 1550 m and significantly at 1600 m.

The 3D modeling showed that while maximum concentrations were not consistent across elevations, the southwestern part maintained the highest overall values and spatial continuity.

These findings confirm the geological variability within the deposit and suggest the importance of elevation-based extraction strategies.

Before initiating the modeling process, it is essential to collect comprehensive information about the target deposit. This includes the results of geological exploration, geophysical surveys, and geochemical analyses, with particular emphasis on borehole data, concentration of the valuable component, structural elements, and surface outcrops. All data must be accurately referenced to a unified coordinate system, which is critical for reliable 3D modeling.

In this case, the UTM Zone 38 coordinate system and the Baltic Height System were used to determine the positions of borehole collars and all depth-specific points within the boreholes. The UTM (Universal Transverse Mercator) system is a global cartographic projection that divides the Earth’s surface into 60 zones, each covering 6° of longitude. UTM Zone 38 covers the longitudes from 42°E to 48°E and is used for areas falling within this range (for example, parts of the Caucasus, Azerbaijan, eastern Turkey, and northern Iran).In this system, coordinates are expressed in meters:

Easting (X) — the distance in meters eastward from the central meridian of the zone (with a “false easting” of 500,000 m applied to avoid negative values).

Northing (Y) — the distance in meters northward from the equator (for the Northern Hemisphere). Thus, the unit of measurement in UTM Zone 38 is meters, which makes it convenient for practical applications in geodesy, mining, and infrastructure monitoring. [5].

Station coordinates were referenced to the fourth-order national geodetic network. To obtain the necessary geological information at the Tulallar deposit, a total of 152 boreholes were drilled, with a combined length of 17,705.55 meters.

The construction of a 3D model in Surfer software begins with the generation of a base surface, which represents the terrain of the study area [6]. A crucial step at this stage is the creation of grid files by interpolating discrete elevation data from borehole collar locations. This process transforms individual measurement points into a continuous surface, representing the spatial distribution of the selected parameter.

For interpolation, the Kriging geostatistical method is applied, as it is considered the most scientifically justified approach for deposit modeling. The resulting surface provides a clear representation of the terrain morphology in the area where data were collected [7, 8, 9].

The input of coordinates, collar elevations, and component concentrations at various depths along each borehole is carried out using Surfer’s Drillhole tool (see Figure 2). This enables the addition of a borehole layer onto the base surface and facilitates the generation of an initial 3D visualization of the component’s distribution along the borehole trajectories (see Figure 3). The point-based data displayed in the model represent the concentration of the valuable component within the individual boreholes [10].

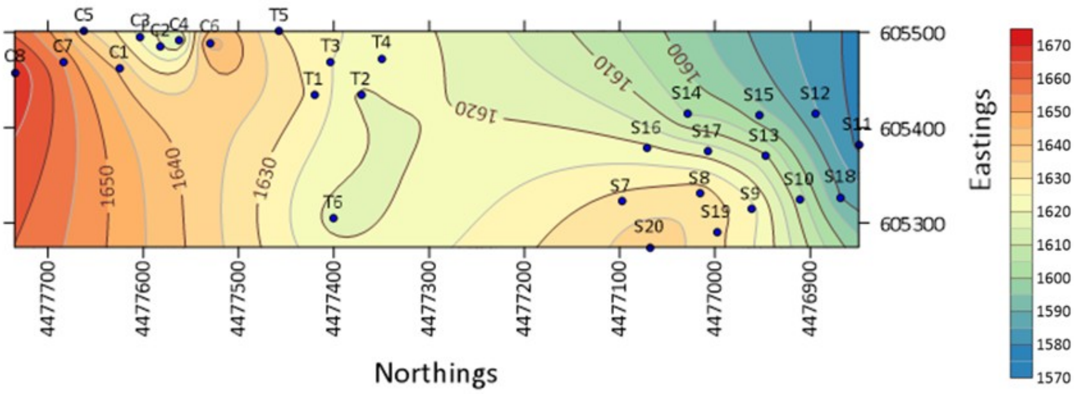


Figure 2 – Input of borehole data using the Drillhole tool in Surfer (UTM Zone 38 coordinate system in meters)

The Surfer software package provides advanced capabilities for the visualization of volumetric objects, including isometric zones representing specific concentrations of valuable components. This functionality is critically important for comprehensive geological modeling [11, 12].

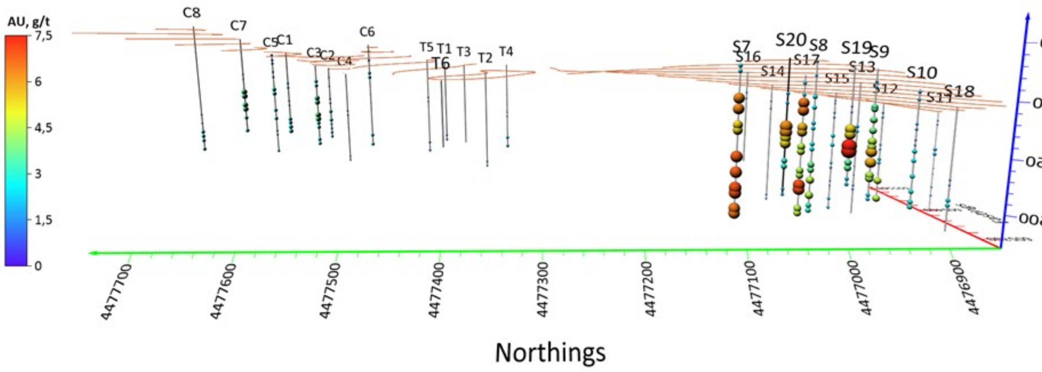


Figure 3 – Initial 3D visualization of component concentration along borehole depth (UTM Zone 38 coordinate system in meters)

To implement such 3D representations, careful preparation and accurate import of raw data are required, an example of which is illustrated in Tabl.1. A key element of this process is the spatial referencing of each measurement point. This involves assigning X and Y planar coordinates along with Z-values that reflect absolute elevation, calculated based on the depth of sample collection within each borehole. This ensures that data are correctly positioned in three-dimensional space [13, 14, 15].

Each spatially referenced point is associated with a specific concentration value of the valuable component, and its variation is tracked along the borehole length. The aggregate dataset serves as the foundation for constructing high-accuracy grid surfaces, which are then visualized to represent the volumetric distribution of the ore body and its qualitative characteristics.

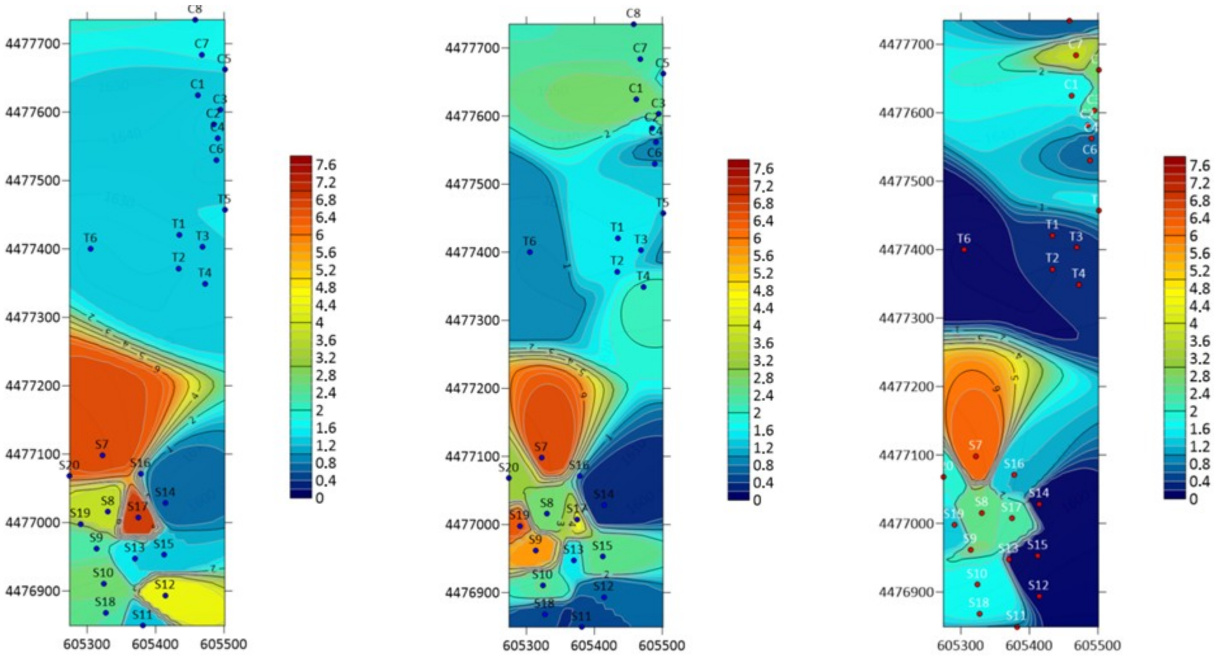
Table 1 – Sample dataset of borehole drilling results with spatial coordinates and corresponding gold concentration values (C Value) for 3D modeling.

Hole ID	X	Y	Z	C Value
S7	605322	4477098	1632	0.00
S7	605322	4477098	1630	2.40
S7	605322	4477098	1625	2.40
S7	605322	4477098	1600	6.30
S7	605322	4477098	1590	6.30
S7	605322	4477098	1575	5.40
S7	605322	4477098	1570	5.40
S7	605322	4477098	1545	6.80
S7	605322	4477098	1530	6.80
S7	605322	4477098	1515	7.00
S7	605322	4477098	1510	7.00
S7	605322	4477098	1495	6.50
S7	605322	4477098	1490	6.50
S8	605331	4477016	1633	1.70
S8	605331	4477016	1620	1.70
S8	605331	4477016	1600	2.60

The import of pre-processed input data into Surfer allows the generation of a two-dimensional contour map that displays the spatial distribution of gold concentration in the form of isolines. Each isoline on this map connects points with equal gold content, thereby visualizing the horizontal distribution patterns of the component within the subsurface [16].

A key advantage of this approach is the ability to dynamically analyze vertical variations in gold distribution by adjusting the elevation of the slicing plane (see Figure 4). By changing this slicing height, a series of contour maps can be generated for different depth levels, enabling a detailed examination of how the position, shape, and dimensions of ore bodies evolve with depth, as well as revealing the internal heterogeneity of gold distribution throughout the deposit.

This method is particularly effective for visualizing the morphology of ore deposits and for identifying zones of elevated mineral concentration [17].



Z=1500 m Z=1550 m Z=1600 m

Figure 4 – Gold concentration distribution at different depth slices, illustrating the spatial variability and internal structure of the ore body within the Tulallar deposit

The next stage of modeling involves the creation of a spatial visualization of the distribution of the valuable component, implemented in Surfer using the integrated "3D View" functionality. The 3D View tool converts the interpolated Grid data into volumetric models in the form of isosurfaces. An isosurface is the three-dimensional analogue of a contour line, connecting all points in space that share the same concentration value of the valuable component [18, 19, 20].

This feature enables the construction of a volumetric representation of any user-defined industrial or cut-off concentration, displaying it as a solid body within the subsurface. For instance, an isosurface can be generated to represent the minimum economically viable concentration of gold, thus visualizing the boundary of the industrial ore body.

At this site, the minimum profitable concentration is defined as 2.5 g/t of gold. Based on this criterion, a three-dimensional model was developed to visualize the spatial distribution of zones with gold concentrations equal to or exceeding this threshold (Figure 5).

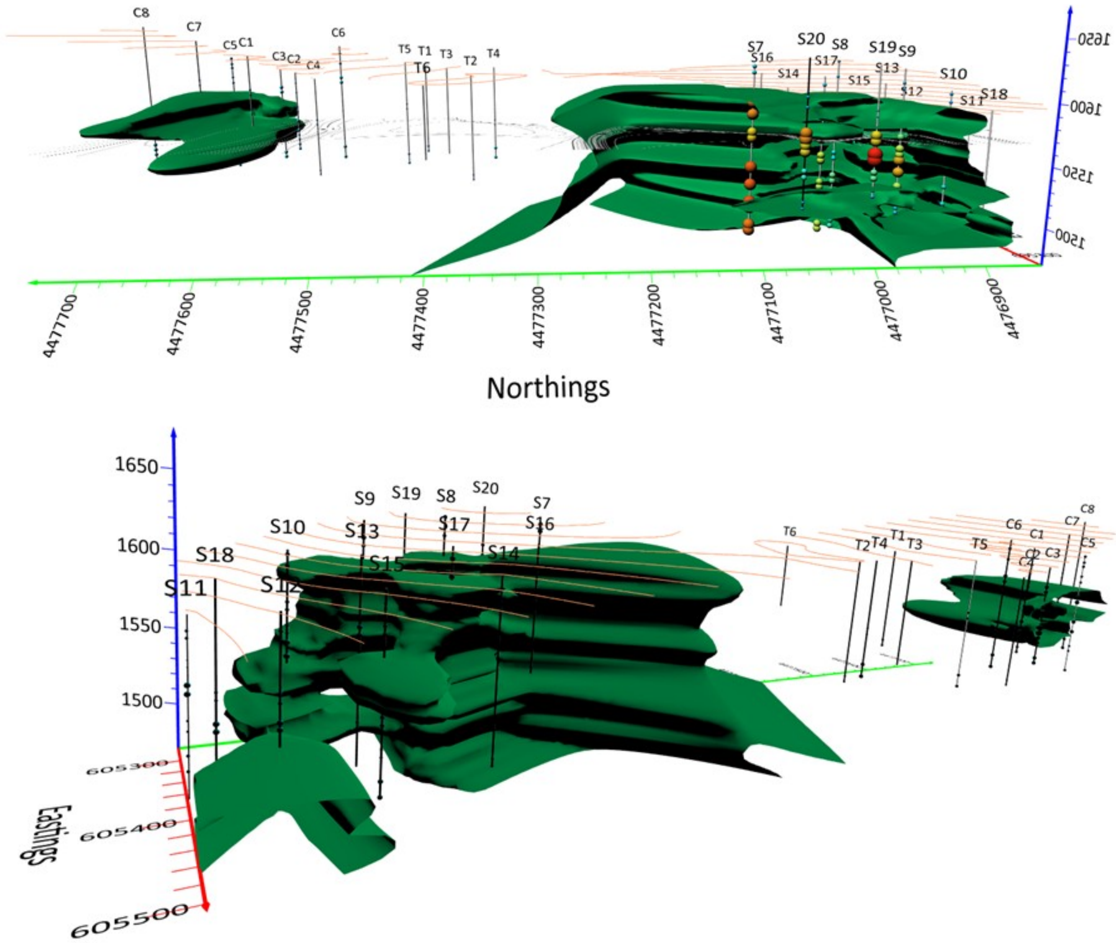


Figure 5 – 3D model of the spatial distribution of areas with a gold concentration of 2.5 g/t from different perspectives (m)

In addition, the 3D View tool offers a wide range of interactive features such as rotation, scaling, translation, and adjustment of viewing angles, allowing users to explore non-obvious morphological features and spatial relationships within the deposit. For comprehensive analysis, Surfer provides the capability to overlay multiple isosurfaces corresponding to different concentration levels. For illustration and further evaluation, the following gold concentration thresholds were selected: 2.5 g/t (green), 4.5 g/t (yellow), and 6.5 g/t (red) (Figure 6).

This approach enables visual assessment of the spatial distribution dynamics of gold concentrations within a defined volume, offering a clearer understanding of high-grade zones and their relationships to the surrounding geology.

Based on the analysis of data and the 3D visualization presented in Figure 12, it was established that gold concentration varies with elevation. Specifically, at an elevation of 1500 meters, the central and northern parts of the study area are dominated by concentrations in the range of 1–1.5 g/t, while in the southwestern region concentrations reach a maximum of 6.5 g/t.

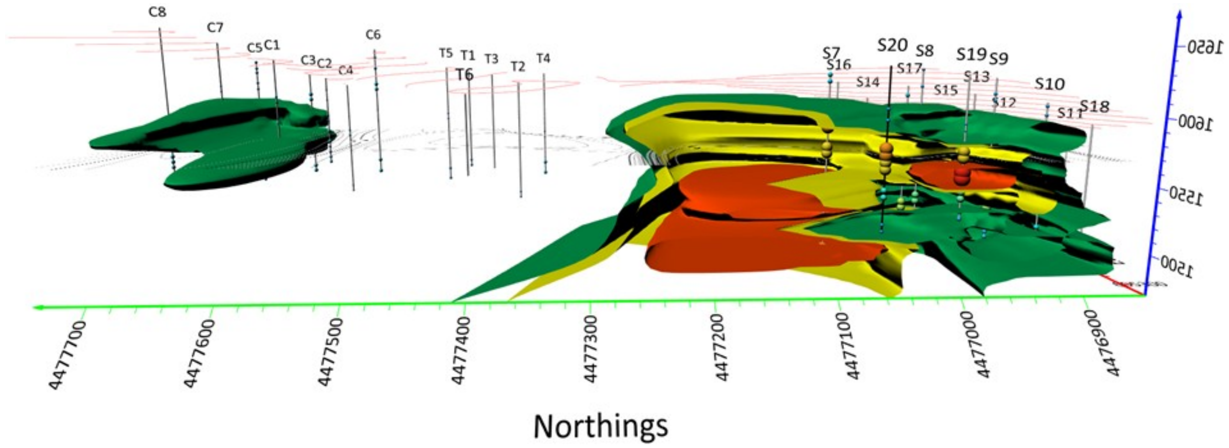


Figure 6 – Three-dimensional model of the subsurface distribution of gold at varying concentrations: 2.5 g/t (green), 4.5 g/t (yellow), and 6.5 g/t (red), (m)

At an elevation of 1550 meters, the spatial distribution changes slightly. Gold concentration in the central area remains stable, while the northern section shows an increase up to 2.5 g/t. The high-concentration zone in the southwest persists, although its spatial extent slightly decreases. The southeastern part of the deposit is predominantly characterized by low concentrations at this level.

At 1600 meters, corresponding to the horizons closer to the surface, there is a general decline in gold concentration across the entire study area. Nevertheless, the southwestern section remains the most productive, with concentrations in the range of 4.5–5.5 g/t.

Additionally, the study identified extreme values of gold concentration within the deposit. The lowest concentration is 0.5 g/t, primarily found in the central zone, while the highest concentration, 7.5 g/t, was recorded in borehole S19, located in the southwestern zone at an elevation of 1560 meters (Figure 7).

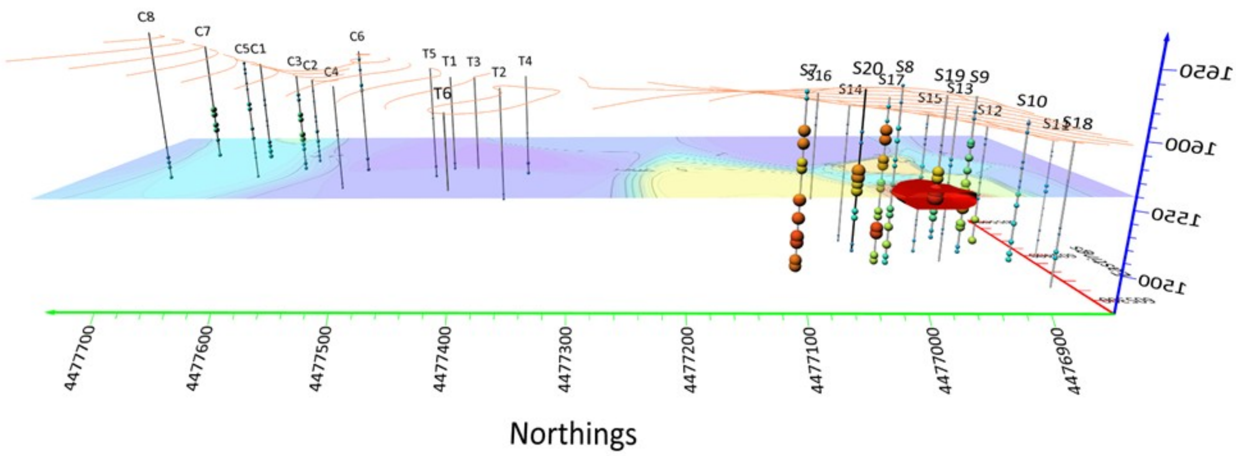


Figure 7 – Area with the highest concentration (m)

The conducted analysis demonstrated that gold concentrations in the southwestern part of the study area significantly exceed those observed in the central and northern zones. This finding supports the conclusion that the southern zone is the most promising for further development, with potential expansion in the northwestern direction.

Thus, by varying both elevation and concentration data, it is possible to perform a comprehensive and accurate analysis of the deposit. This approach not only enables the identification of optimal depths for mining, but also provides a rational basis for selecting appropriate extraction technologies. The resulting data form a solid foundation for reliable resource estimation and strategic planning of deposit exploitation.

4. Conclusions

The study confirms that geodetic monitoring and GIS-based spatial analysis are essential for modern deposit evaluation. Key results include the development of a high-resolution 3D model of gold concentration zones. The southwest zone was identified as the most promising for further development due to its consistently high gold content. Vertical zoning was found to significantly affect concentration, reinforcing the need for depth-sensitive planning. The methodology demonstrated here allows for accurate reserve estimation, strategic mining planning, and reduced environmental impact.

This integrated approach represents a significant improvement over traditional methods and supports more rational and sustainable resource exploitation.

Conflict of interest

Authors state no conflict of interest.

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ІНТЕГРАЦІЯ ГІС ТЕХНОЛОГІЙ ТА ГЕОДЕЗИЧНОГО МОНІТОРИНГУ ДЛЯ МОДЕЛЮВАННЯ ЗОЛОТОРУДНОГО РОДОВИЩА ТА ПЛАНУВАННЯ ГІРНИЧИХ РОБІТ

Зуєвська Н., Косенко Т., Шукюрлю Е., Гаджієв П., Шукюрлю Н.

Анотація. У цьому дослідженні представлено поглиблений геопросторовий та геодезичний аналіз золоторудного родовища Туллалар із використанням сучасних технологій 3D-моделювання. У якості основи для побудови детальної тривимірної моделі, створеної в програмному забезпеченні Golden Software Surfer, використано базу даних з 152 свердловин загальною глибиною 17 705,55 метрів. Метою дослідження було візуалізувати просторовий розподіл золотовмісних руд і оцінити варіабельність концентрацій золота на різних глибинах та у різних геологічних зонах.

Для точного відображення підповерхневої мінералізації були застосовані сучасні ГІС-інструменти, зокрема модуль Drillhole та метод інтерполяції крігінгом. Аналіз виявив виражену зональність, особливо у південно-західному секторі, де концентрації золота досягали 7,5 г/т, що значно вище, ніж у центральній та північній частинах родовища. Додавання топографічних шарів, ізоповерхонь та контурних карт забезпечило динамічну інтерпретацію морфології рудного тіла, зональності та розподілу по глибині.

Побудовані 3D-моделі дозволили не лише ідентифікувати економічно доцільні мінералізовані зони, але й візуалізувати їхню просторову конфігурацію з високою точністю. Такі моделі дозволяють геологам оцінювати взаємозв'язок між концентрацією руди та висотними відмітками рельєфу, сприяючи прийняттю стратегічних рішень у процесі розвідки та планування гірничих робіт.

Інтегрований геодезичний та ГІС-підхід виявився ефективним для візуалізації геометрії мінералізованих зон, придатних для подальшого освоєння. Результати підтверджують, що південна зона має найвищий потенціал для майбутньої експлуатації, що має важливе значення для більш точної оцінки ресурсів, оптимізації видобувних стратегій та екологічно стійкого планування. Проведений аналіз показав, що концентрація золота в південно-західній частині досліджуваної території суттєво перевищує аналогічні показники в центральній і північній частинах.

Таким чином, варіюючи висотні дані та концентрації, можна здійснити комплексний та точний аналіз родовища. Такий підхід дозволяє не лише визначити оптимальні глибини для видобутку, а й обґрунтовано вибрати відповідні технології вилучення. Отримані дані формують надійну основу для оцінки запасів та стратегічного планування розробки родовища.

Ключові слова: золоторудне родовище, 3D-моделювання, ГІС-технології, інтерполяція крігінгом, дані свердловин, оцінка мінеральних ресурсів, геодезичний моніторинг, просторовий аналіз, програмне забезпечення Surfer, візуалізація рудного тіла.