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GEOLOGICAL STRUCTURE AND MINERALIZATION FEATURES OF THE SOYUDLU (ZOD) GOLD DEPOSIT IN GARABAGH (KALBAJAR DISTRICT)

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Summary. The Soyudlu (Zod) gold deposit is one of the major gold-bearing objects of the Lesser Caucasus. This study focuses on the geological structure of the deposit, the spatial distribution of mineralized bodies, and the principal structural and hydrothermal factors controlling ore localization. Particular attention is given to graphical interpretation, because the geometry of ore bodies and their spatial relationship with fault systems, dikes, and hydrothermal alteration zones provide key evidence for understanding the mineralization pattern. The deposit is confined to the central and southeastern part of the Garamanly–Zod–Soyudlu anticlinal structure within the Goycha-Hakari geostructural zone and belongs to the ophiolitic domain of the Lesser Caucasus. The ore field is characterized by gabbroic and ultrabasic rocks, rhyodacitic dikes, and a structurally complex system of north–south, northwest–southeast, and northeast–southwest faults. Graphical materials show that mineralization is concentrated in a limited number of principal ore bodies and follows a distinct tectonic framework. Hydrothermal alteration is represented mainly by quartz-carbonate and talc-carbonate assemblages developed along pre-existing structural dislocations. Quantitative descriptors of structural ordering, ore-body concentration, and alteration-zone variability support the interpretation that Soyudlu is a structurally controlled hydrothermal gold system. The combined interpretation of the location scheme, ore-body distribution map, isometric diagram, and three-dimensional views confirms that the deposit may be regarded as an important geological model for understanding structurally focused gold mineralization in the Lesser Caucasus.

Keywords: *Soyudlu (Zod), gold deposit, Lesser Caucasus, structural control, hydrothermal alteration, ore bodies, geological interpretation*

Introduction

Gold mineralization in the Lesser Caucasus is characterized by a strong dependence on regional tectonic setting, lithological contrasts, and the long-term evolution of hydrothermal systems. Within this metallogenic framework, the Soyudlu (Zod) deposit occupies a particularly important position because it combines large-scale mineralization with a geologically complex internal structure. The deposit is located in the Kalbajar region and belongs to the Goycha-Hakari geostructural zone, specifically to the central and southeastern part of the Garamanly–Zod–Soyudlu anticlinal structure. Its regional and local geological position is shown in Fig. 1. It is associated with the ophiolitic domain of the Lesser Caucasus and is localized in sedimentary rocks and intrusive bodies related to regional volcanism. This geological position alone makes the deposit significant as a natural example of structurally controlled hydrothermal gold mineralization (Шихалибейли, 1964, 1966; Гасанов, 1985)

Previous investigations and regional geological background

Previous geological studies of the Lesser Caucasus provide an important basis for interpreting the Soyudlu (Zod) deposit. The broader geological framework of Azerbaijan, including regional stratigraphic correlations, has also been discussed in earlier syntheses (Ализаде и др., 1989). The regional tectonic evolution, magmatism and structural segmentation of the eastern Lesser Caucasus were described in detail by Shikhalibeyli (Шихалибейли, 1964, 1966), while the ophiolitic complexes of the Lesser Caucasus and their role in the regional tectonic architecture were systematized by Hasanov (Гасанов, 1985). The Sevan-Garabagh / Goycha-Hakari ophiolitic zone and the metallogenic significance of ultrabasic and gabbroic associations were also discussed in earlier works by Baba-Zade (Баба-заде, 1974) and Baba-Zade and Malyutin (Баба-заде, Малютин, 1967). These studies form the regional geological framework within which the Soyudlu (Zod) deposit can be considered as part of a structurally complex ophiolitic and ore-bearing system of the Lesser Caucasus.

Later generalizations on noble-metal ore-magmatic systems and gold-bearing sulfide fields of the Lesser Caucasus showed that gold mineralization in the region is commonly linked with island-arc paleosystems, magmatism, hydrothermal alteration and structural control (Баба-заде, Абдуллаева, 2012; Баба-заде и др., 2015). However, despite the extensive regional background, the spatial geometry of ore bodies, their relationship with hydrothermal alteration zones and the practical value of three-dimensional geological interpretation for the Soyudlu (Zod) deposit still require additional integrated analysis. The present study therefore builds upon previous regional investigations and focuses on figure-based interpretation of ore-body distribution and structural-hydrothermal controls within the deposit.

A major difficulty in describing Soyudlu is that the deposit cannot be adequately understood through text alone. Its internal architecture is controlled by several fault systems of different orientation, by the spatial relationship between dikes and ore bodies, and by the uneven distribution of hydrothermal alteration. In such deposits, the geometry of mineralized bodies is as important as their mineralogical composition. For this reason, graphical interpretation plays a central role in the present study. The location scheme, ore-body distribution map, isometric diagram, and three-dimensional views are not supplementary illustrations only; they form the visual framework through which the structural organization of the deposit can be understood.

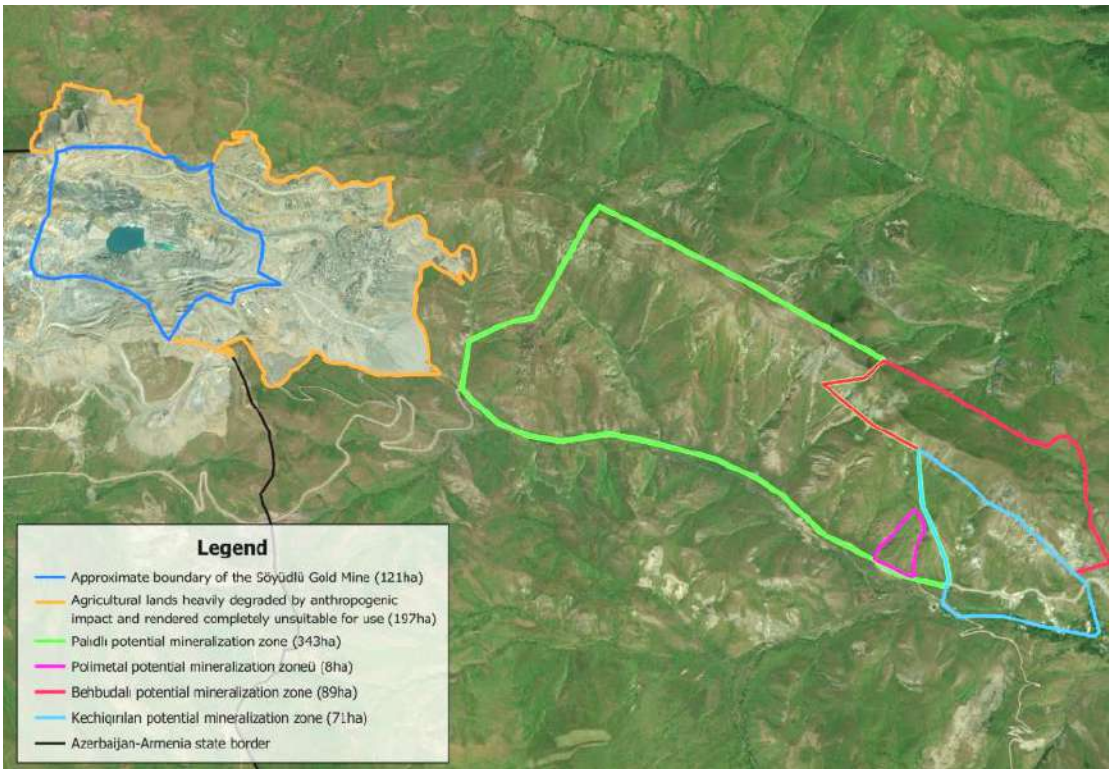

Fig. 1. Geological location of the Soyudlu (Zod) deposit

The geological description of the deposit shows that the ore field is affected by north–south, northwest–southeast, and northeast–southwest fault systems. These structures complicate the internal architecture of the deposit and, at the same time, appear to control the distribution of hydrothermal alteration and ore localization. The host rocks include gabbroic, ultrabasic, and rhyodacitic units, while hydrothermal alteration is represented mainly by quartz-carbonate and talc-carbonate assemblages. The mineralized system is therefore the result of the interaction of tectonic preparation, favorable host lithologies, and fluid-related ore deposition. The principal ore bodies are not distributed evenly across the ore field, but are concentrated in a limited number of structurally favorable domains. This pattern is one of the central observations examined in the article.

Another important reason to study Soyudlu is that the deposit illustrates how several scales of geological evidence can be integrated. At the regional scale, it belongs to a well-defined structural zone of the Lesser Caucasus. At the deposit scale, it is organized into a system of major and minor ore bodies. At the internal ore-field scale, it shows strong variability in alteration thickness, vein orientation, and structural continuity (Баба-заде, 1974; Баба-заде, Абдуллаева, 2012; Баба-заде и др., 2015).

A scientifically useful description of such a deposit should therefore move from regional position to deposit geometry and then to ore-body scale. This is why the article is organized around both geological description and figure-based interpretation.

The aim of this study is to characterize the geological structure and mineralization features of the Soyudlu (Zod) gold deposit and to identify the principal structural and hydrothermal factors controlling ore-body localization. Particular attention is given to the interpretation of graphical materials prepared during geological investigations within AzerGold CJSC studies, because these materials make it possible to relate ore bodies directly to structural corridors, alteration zones, and intrusive elements. The study does not attempt to present an internal technical report or a production-based evaluation of the deposit. Instead, it develops a geological interpretation focused on the spatial organization of mineralization and on the structural model that best explains that organization (Баба-заде, Абдуллаева, 2012; Баба-заде и др., 2015).

Materials and Methods

This study was based on three complementary groups of materials. The first group consisted of previously published geological works on the eastern Lesser Caucasus, the ophiolitic complexes of the Lesser Caucasus, the Sevan-Garabagh / Goycha-Hakari zone, and noble-metal ore-magmatic systems (Шихалибейли, 1964, 1966; Гасанов, 1985; Баба-заде, 1974; Баба-заде, Малютин, 1967; Баба-заде, Абдуллаева, 2012; Баба-заде и др., 2015). The second group consisted of published methodological sources used to define the general scientific framework of the work, including the role of GIS and mining-geological information systems in deposit interpretation (Мамедов и др., 2020). The third group consisted of graphical materials prepared during geological studies of the Soyudlu (Zod) deposit within AzerGold CJSC. These materials formed the direct basis for deposit-scale interpretation. The article therefore combines a conventional academic approach with figure-based geological analysis derived from applied exploration materials.

The methodological approach was designed around the principle that a structurally complex deposit must be analyzed in both two-dimensional and three-dimensional form. For this reason, the study did not rely on a single figure or a single type of description. Instead, four key illustrations were treated as interconnected analytical elements. Fig. 1, the location and geological setting scheme, was used to establish the regional and local structural position of the deposit. Fig. 2, showing the distribution of ore bodies, was used to evaluate how mineralization is arranged within the deposit. Fig. 3, the isometric diagram, was used to examine the three-dimensional geometry of the principal ore bodies. Fig. 4, showing eastern and southern views of the mineralized bodies, was used to assess spatial continuity, relative position, and structural alignment in depth. Each of these figures contributed a different level of evidence, and only their combined interpretation allowed a coherent model of ore localization to be proposed.

The three-dimensional ore-body forms presented in the figures were not treated as independent images. They were obtained by geological interpretation and wireframe modelling in GEOVIA Surpac on the basis of geological mapping materials, ore-body contours, lithological boundaries, structural observations, geological sections and drilling-derived geological information available for the Soyudlu (Zod) deposit. The modelling was carried out by the authors using the geological investigation materials of AzerGold CJSC. Therefore, the colours and separate wireframes shown in the 3D views are used primarily to distinguish individual ore bodies and to make their spatial position visible; they are not intended to indicate separate ore grades, metallurgical classes or economic categories unless this is stated separately in the figure caption.

The interpretation began with the regional and local geological position of the deposit. The location scheme was examined not simply as a cartographic background, but as a structural reference for the rest of the study. It was used to place the deposit within the Goycha-Hakari geostructural zone and the Garamanly–Zod–Soyudlu anticlinal structure, and to establish the tectonic context within which later ore-forming processes occurred. This step was important because the meaning of the ore-body geometry cannot be properly understood without reference to the larger structural framework.

The second stage of the study focused on ore-body distribution. The ore-body map was examined to identify the principal mineralized domains, to compare the relative importance of major and minor ore bodies, and to assess whether mineralization was dispersed or concentrated. Special attention was given to bodies 1, 4, 16, and 23, because the geological materials indicate that these bodies account for the dominant share of known mineralization. The figure was interpreted not only descriptively, but also comparatively: the position of these bodies was considered in relation to surrounding smaller ore zones and in relation to the structural corridors described in the geological text. This allowed the deposit to be viewed as a hierarchical mineralized system rather than a simple collection of isolated bodies.

The colours used for the ore bodies in Figs. 2-4 are intended primarily for visual differentiation of individual mineralized bodies and for separating the principal ore bodies from smaller associated bodies. They should not be interpreted as independent metallurgical, mineralogical, or grade classes unless this is specifically stated in the figure legend. Bodies 1, 4, 16, and 23 are emphasized because they are distinguished by a combination of criteria: relative contribution to known mineralization, spatial continuity, three-dimensional persistence, and their position within the main structural and hydrothermal alteration corridors. The remaining mineralized bodies are shown separately in order to preserve their geological significance as secondary or peripheral mineralized zones that may be important for further exploration.

The third stage involved three-dimensional interpretation. The isometric diagram and the eastern and southern views were treated as the main source for understanding ore-body morphology, dip, elongation, and mutual position. These figures were analyzed together rather than separately. The isometric view was particularly useful for recognizing the overall geometry of the ore bodies and for identifying whether they form an ordered spatial system. The additional side views helped to clarify how these bodies continue in depth and how their position changes when observed from different directions. This stage was critical because many structural relationships that are only weakly visible in plan view become clearer when the bodies are examined in three-dimensional perspective.

The fourth stage consisted of integrating the graphical observations with the textual geological description. The geological text was used to identify the main host rocks, the role of north–south and east–west dike systems, the development of quartz-carbonate and talc-carbonate alteration, and the distribution of fracture and vein sets. These observations were then compared with the graphical geometry of the ore field. In this way, the study moved from descriptive geology to interpretive geology: the text provided geological meaning, while the figures showed spatial expression. The purpose of this stage was to test whether the deposit could be consistently interpreted as a structurally controlled hydrothermal system (Юнгмейстер и др., 2024).

In interpreting the relationship between faults, hydrothermal alteration and ore localization, the study relies on the established regional geological understanding of the Lesser Caucasus rather than on unrelated stratigraphic works. The occurrence of quartz-carbonate and talc-carbonate alteration along tectonic dislocation zones is considered in the context of ophiolitic complexes, ultrabasic and gabbroic rocks, and noble-metal ore-magmatic systems described for the Lesser Caucasus (Гасанов, 1985; Баба-заде, Малютин, 1967; Баба-заде, Абдуллаева, 2012). Therefore, the alteration zones are interpreted as fluid-conducting structural corridors that created favorable conditions for the localization of gold mineralization.

The factual basis of the interpretation includes geological mapping materials, structural observations, lithological boundaries, ore-body outlines, drilling-derived geological sections, assay and geochemical information where available, and three-dimensional geological modelling materials prepared during investigations of the Soyudlu (Zod) deposit. The spatial interpretation was carried out by comparing mapped faults, dike systems, hydrothermal alteration zones and ore-body contours in plan view and in three-dimensional projections. In this approach, the 3D model is not treated as an independent result separated from field geology; it is used as a visual and analytical synthesis of mapping, drilling and geological interpretation data.

The interpretation procedure consisted of several consecutive stages: first, regional tectonic and ophiolitic setting was compared with earlier studies of the Lesser Caucasus; second, the local structural pattern of the deposit was examined on geological schemes and sections; third, ore bodies were compared with the position of fault-controlled permeability zones and hydrothermal alteration halos; fourth, three-dimensional views were used to verify the continuity, dip and relative position of the main ore bodies; finally, the obtained spatial regularities were assessed in terms of their possible application to further exploration and mining-geological planning.

From a methodological point of view, the present study is based on the integrated interpretation of geological schemes, ore-body distribution maps, and three-dimensional views obtained during geological investigations of the Soyudlu (Zod) deposit conducted within the framework of AzerGold CJSC research activities. This approach makes it possible to examine the relationship between structural framework, hydrothermal alteration, and the spatial organization of mineralization at different scales. In this context, the figures are treated not merely as illustrative material, but as analytical components used to evaluate ore-body geometry, continuity, and structural alignment.

Accordingly, the methodological emphasis of the paper is placed on geological interpretation supported by graphical analysis. The location scheme is used to define the regional and local structural setting of the deposit, the ore-body distribution map is used to identify the principal mineralized domains, and the isometric and directional views are used to assess the three-dimensional geometry of the ore bodies. The combined interpretation of geological description and graphical materials provides the basis for considering the Soyudlu (Zod) deposit as a structurally controlled hydrothermal gold system.

The theoretical basis of this study is that gold mineralization within the Soyudlu (Zod) deposit is structurally controlled and spatially associated with fault systems, hydrothermal alteration zones, and favorable host lithologies. This interpretation is consistent with the regional tectonic and magmatic framework of the eastern Lesser Caucasus described by Shikhalibeyli (Шихалибейли, 1966), the ophiolitic setting of the Lesser Caucasus summarized by Hasanov (1985), and the metallogenic significance of the Sevan-Garabagh / Goycha-Hakari ophiolitic zone discussed by Baba-Zade (Баба-заде, 1974). The geological description of the deposit indicates that the ore field is affected by north-south, northwest-southeast, and northeast-southwest fault systems, while hydrothermal alteration developed along pre-existing tectonic dislocations and is mainly represented by quartz-carbonate and talc-carbonate assemblages. In addition, the principal ore bodies are concentrated in a limited number of structurally favorable domains, which suggests that mineralization was localized through focused fluid migration rather than through uniform impregnation of the host rocks (Баба-заде, Абдуллаева, 2012; Баба-заде и др., 2015).

In this context, the hydrothermal alteration halos are considered not as isolated lithological features, but as indicators of ore-forming fluid pathways. Quartz-carbonate alteration is interpreted as being most closely related to fractured and permeable structural zones where quartz-sulfide veining and gold mineralization were concentrated. Talc-carbonate alteration is associated mainly with ultrabasic and ophiolitic host rocks affected by hydrothermal fluids along tectonic dislocations. The spatial coincidence of these alteration assemblages with the principal ore bodies indicates that mineral formation occurred during stages of structurally focused hydrothermal activity rather than as a uniform alteration of the host rocks.

Therefore, the relationship between alteration halos and mineralization is assessed through three linked criteria:

(i) their position relative to major faults and fracture corridors;
(ii) their spatial overlap with the principal ore bodies, especially bodies 1 and 16; and
(iii) the variability of alteration-zone thickness, which reflects changes in permeability and intensity of fluid circulation. This explanation clarifies why the quartz-carbonate and talc-carbonate halos are important for the genetic interpretation of the deposit and for recognizing zones that may be prospective during subsequent exploration.

In order to support the geological interpretation with quantitative descriptors, the present study applies a limited set of structural and geometrical indicators. These indicators are used only as supplementary descriptive tools and are not presented as new calculation methods or as reserve-estimation procedures. The entropy calculation follows the general information-entropy approach proposed by Shannon (1948), while the concentration and contrast ratios are applied here as simple statistical descriptors commonly used to compare the relative dominance and variability of geological objects. The use of information-based quantitative descriptors in mineral-related spatial interpretation is also consistent with approaches discussed by Abedi (2021), although in the present study these indicators are applied only as supplementary tools for geological interpretation. In mineral-deposit studies, such numerical descriptors should be interpreted together with geological mapping, drilling information, three-dimensional modelling and expert geological judgement rather than separately from the geological context (Journel and Huijbregts, 1978; Sinclair and Blackwell, 2002). For this reason, the calculations in this paper are used to characterize structural ordering, ore-body concentration and alteration-zone variability within the Soyudlu ore field, but the final interpretation is based on the integrated analysis of factual geological materials and Surpac-based 3D models.

The first indicator describes the structural ordering of the mineralized vein system. According to the geological interpretation of the deposit and the regional structural framework of the Lesser Caucasus, the dominant orientation of mineralized veins reflects the influence of tectonic anisotropy developed within the ophiolitic and island-arc related systems of the region (Шихалибейли, 1966; Гасанов, 1985; Баба-заде, 1974; Баба-заде и др., 2015). Approximately 75% of quartz-sulfide veins are concentrated within the 60°-120° azimuth interval, around 15% within 30°-60°, and less than 10% are close to the north-south direction. To express the degree of structural ordering numerically, Shannon entropy was used in accordance with the general entropy concept of Shannon (1948):

$$H = -\sum_{i=1}^{n} p_i \ln\ p_i,$$

where p_i is the proportion of veins in each azimuth class.

For the grouped data:

$$H = -(0.75\ln\ 0.75 + 0.15\ln\ 0.15 + 0.10\ln\ 0.10) = 0.7306$$

For three structural classes, the maximum possible entropy is

$$H_{\max} = \ln\ 3 = 1.0986$$

and the normalized evenness coefficient is

$$J = \frac{H}{H_{\max}} = \frac{0.7306}{1.0986} = 0.665$$

The second indicator characterizes the concentration of mineralization within the principal ore bodies. Ore bodies 1, 4, 16 and 23 were distinguished as principal bodies on the basis of a combined geological criterion rather than on colour alone. The selection is based on their relative share in known mineralization, greater spatial continuity in plan and section, clearer expression in the Surpac 3D wireframe model, association with the main structural-alteration corridors, and their potential practical importance for further exploration and mine planning. In this sense, the four bodies are treated as the dominant geological objects of the current model, while the remaining mineralized bodies are considered smaller or less continuous occurrences requiring additional verification during future exploration. The geological description states that ore bodies 1, 4, 16 and 23 account for up to 80% of the known mineralization. This relationship may be expressed as a concentration ratio:

$$\mathrm{CR}_4 = \frac{\mathrm{M}_{\mathrm{main}}}{\mathrm{M}_{\mathrm{total}}}$$

where $\mathrm{M}_{\mathrm{main}}$ is the proportion of mineralization hosted by the four principal ore bodies and $\mathrm{M}_{\mathrm{total}}$ is the total known mineralization. For Soyudlu:

$$\mathrm{CR}_4 = \frac{80}{100} = 0.80$$

or 80%. A complementary concentration coefficient may also be expressed as:

$$\mathrm{K}_{\mathrm{c}} = \frac{\mathrm{M}_{\mathrm{main}}}{\mathrm{M}_{\mathrm{minor}}} = \frac{80}{20} = 4.0$$

This means that, within the current geological model, the four principal ore bodies contain a much larger share of the known mineralization than the remaining bodies taken together. However, this result should not be interpreted as reducing the geological importance of the other approximately 20% of mineralization. From an exploration point of view, smaller mineralized bodies may represent lateral continuations, peripheral branches, blind extensions or less studied parts of the same hydrothermal system. Therefore, these occurrences remain important targets for additional mapping, drilling and geochemical verification. The concentration ratio is used only to show the present hierarchy of ore bodies in the model, whereas the geological significance of both the dominant and subordinate mineralized bodies must be considered in future exploration planning (Sinclair, Blackwell, 2002).

The distinction between the principal four bodies and the remaining mineralized zones is therefore geological and modelling-based, not solely economic or metallurgical. At the present stage, the main criteria are ore-body continuity, size and geometry, structural position, relationship with hydrothermal alteration zones and contribution to the known mineralized volume. Economic parameters and metallurgical characteristics may further refine this classification at later stages, but they should not replace geological interpretation during the exploration stage. For this reason, the remaining 20% of mineralization is retained in the model as geologically meaningful and should be included in further exploration programs.

The third indicator describes the spatial heterogeneity of hydrothermal alteration. The thickness and position of the principal alteration zones were interpreted from geological mapping observations, lithological-structural boundaries, drilling-related geological information and their spatial comparison with ore-body wireframes in GEOVIA Surpac. The geological materials indicate that the thickness of the principal hydrothermal alteration zones varies from about 10 m to 50 m. The thickness contrast ratio was therefore calculated as:

$$K_t = \frac{T_{max}}{T_{min}} = \frac{50}{10} = 5.0$$

In addition, the normalized range of variation was estimated as:

$$\mathrm{V}_{\mathrm{t}} = \frac{\mathrm{T}_{\mathrm{max}} - \mathrm{T}_{\mathrm{min}}}{\mathrm{T}_{\mathrm{max}} + \mathrm{T}_{\mathrm{min}}} = \frac{50 - 10}{50 + 10} = 0.667$$

A simplified mean thickness of the principal alteration zone may be expressed as:

$$\bar{\mathrm{T}} = \frac{\mathrm{T}_{\mathrm{max}} + \mathrm{T}_{\mathrm{min}}}{2} = \frac{50 + 10}{2} = 30\ \mathrm{m}$$

These values show that the hydrothermal zones are strongly heterogeneous in thickness. Such variability indicates that hydrothermal activity was spatially selective and intensified within particular structural segments, most likely where permeability and fluid focusing were greatest. This interpretation is consistent with the observed spatial relationship between alteration zones and principal ore bodies in the central ore block and with the general model of structurally controlled noble-metal hydrothermal systems in the Lesser Caucasus (Баба-заде, Абдуллаева, 2012; Баба-заде и др., 2015).

Taken together, the calculated indicators support one coherent geological interpretation. The non-random orientation of the vein system, the strong concentration of mineralization in a few principal ore bodies, and the marked heterogeneity of hydrothermal alteration all indicate that the Soyudlu (Zod) deposit represents a structurally focused hydrothermal gold system. The role of the calculations in this study is therefore to provide numerical support for the geological model derived from the combined interpretation of textual and graphical materials.

From an applied point of view, the proposed interpretation can be used at the detailed exploration stage to refine the position of additional drill holes, to test the continuity of mineralized zones along fault-controlled corridors, and to distinguish between principal ore bodies and peripheral mineralized occurrences. During the mining-planning stage, the same approach may support the updating of geological models, clarification of ore-body boundaries, and better understanding of the relationship between mineralization, alteration and structural discontinuities. Thus, the regularities identified in this study have both genetic and practical significance.

The practical importance of the Surpac-based ore-body model lies in its ability to convert scattered geological observations into a coherent three-dimensional framework. For exploration, the model helps to identify where additional drill holes should be placed to test continuity along fault-controlled and alteration-controlled corridors. For resource modelling, it provides a basis for updating ore-body boundaries when new drilling and assay data become available. For mining, it supports the interpretation of ore-body geometry, expected continuity, contact zones with host rocks and the relationship between mineralization and structural discontinuities. Consequently, the 3D forms shown in the article are not only illustrative figures; they are practical geological tools for further exploration, model refinement and mine-planning decisions.

Results and Discussion

The results of this study show that the Soyudlu (Zod) gold deposit has a well-defined structural framework that controls both the distribution of mineralization and the geometry of the ore bodies. This conclusion is supported by the geological description of the deposit and by the interpretation of Figs. 1-4, which together provide the main visual basis for understanding the structure of the ore field.

The first important result concerns the regional and local geological setting of the deposit. As shown in Fig. 1, the Soyudlu (Zod) deposit is situated within the Goycha-Hakari geostructural zone and occupies the central and southeastern part of the Garamanly–Zod–Soyudlu anticlinal structure. This figure is important because it places the deposit within its broader tectonic environment and establishes the geological framework in which ore formation occurred. In this respect, Fig. 1 provides the structural context for the interpretation of all other geological relationships discussed in the paper.

The second major result is the non-random distribution of ore bodies within the deposit. This relationship is clearly illustrated in Fig. 2, which shows the spatial arrangement of the main ore bodies. The figure demonstrates that mineralization is not evenly spread across the deposit area. Instead, it is concentrated in a limited number of structurally favorable domains. In particular, ore bodies 1, 4, 16, and 23 occupy the dominant positions within the ore field and represent the main centers of mineralization. This pattern supports the conclusion that the deposit has a clear internal hierarchy, in which several major ore bodies play the leading geological role, while the remaining mineralized zones are of secondary importance.

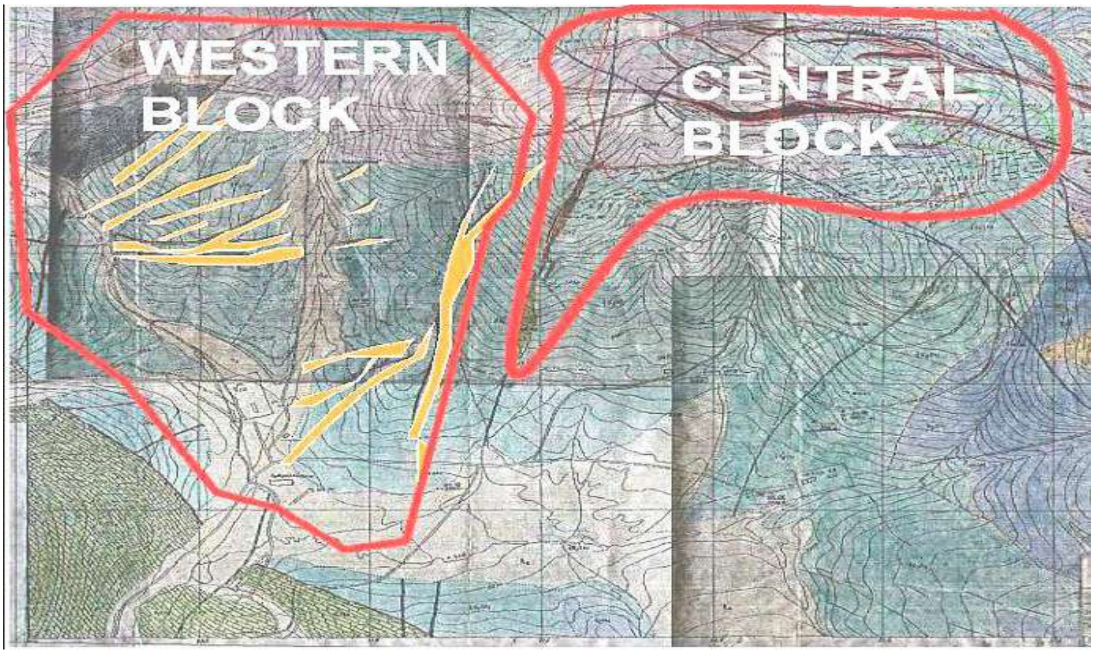

Fig. 2. Spatial distribution of the ore bodies in the Soyudlu (Zod) deposit. The colours are used to distinguish individual ore bodies and their relative spatial position; they do not represent separate ore grades or metallurgical classes. The ore-body contours and spatial relationships were interpreted in GEOVIA Surpac on the basis of geological investigation materials, drilling-related geological information and geological sections of AzerGold CJSC. Compiled by the authors

Fig. 2 is therefore central to the interpretation of ore concentration. It visually supports the idea that mineralization at Soyudlu is selective rather than uniform. From a geological point of view, this means that ore-forming fluids did not affect the deposit evenly but were concentrated in specific structural corridors and favorable host zones. The figure thus provides direct spatial evidence that ore accumulation was focused within a restricted number of major ore-bearing bodies.

The classification shown in Fig. 2 is therefore based on geological and spatial criteria rather than on colour alone. The principal ore bodies are separated from the smaller bodies because they show greater continuity, larger relative contribution to known mineralization and clearer spatial association with the main structural-alteration corridors. At the same time, the smaller bodies are not excluded from the geological model; they represent additional mineralized zones that may indicate lateral or depth extensions of the ore system and should be considered during subsequent exploration planning.

The third major result concerns the three-dimensional geometry of the ore bodies. While Fig. 2 is useful for understanding the distribution of mineralization in plan view, the spatial organization of the deposit becomes much clearer in Fig. 3, which presents the isometric diagram of the ore bodies. This figure shows that the main ore bodies are elongated, ordered in space, and geometrically related to one another. They do not appear as isolated or randomly shaped lenses. Instead, their arrangement suggests structural continuity and a shared tectonic control. This is one of the strongest visual arguments in the article, because Fig. 3 allows the deposit to be understood as a three-dimensional geological system rather than as a simple set of mapped bodies.

This interpretation is further supported by Fig. 4, which presents eastern and southern views of the ore bodies. These views are particularly useful because they allow the reader to assess the dip, relative position, and continuity of the mineralized bodies in depth. In many geological studies, plan-view figures alone do not fully reveal the internal organization of a deposit. In the present case, Fig. 4 provides the additional spatial perspective needed to confirm that the ore bodies form a coherent structural system. Taken together, Figs. 3 and 4 show that the Soyudlu ore field is characterized by spatial order, continuity, and structural alignment.

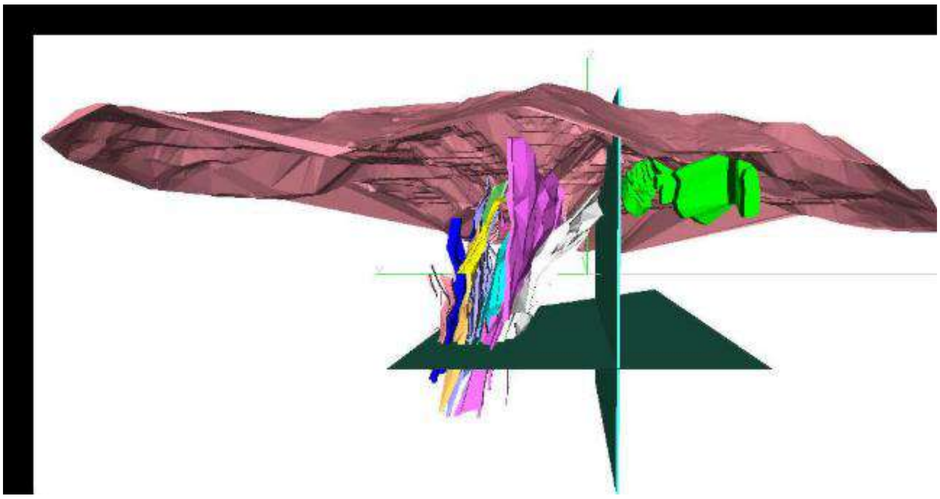

Fig. 3. Isometric diagram of the ore bodies in the Soyudlu (Zod) deposit. The 3D wireframe representation was prepared by the authors in GEOVIA Surpac using geological investigation materials, ore-body contours, geological sections and drilling-derived geological information of AzerGold CJSC

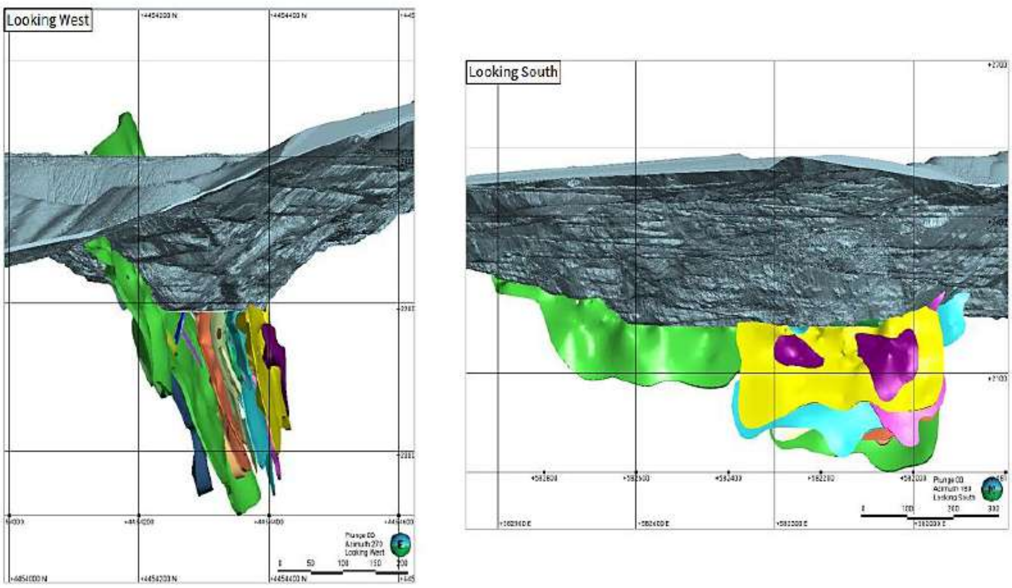

Fig. 4. Eastern and southern views of the ore bodies in the Soyudlu (Zod) deposit (Directional views were generated from the Surpac 3D geological model to assess ore-body dip, continuity and relative spatial position)

Another important result is the close relationship between ore bodies and hydrothermal alteration zones. The central ore block contains two major alteration zones that play a key role in ore localization. The first extends approximately in an east–west direction and varies in thickness from 10 m to 50 m; ore body 1 is located within this zone. The second alteration zone lies to the north, initially follows a similar trend, and later changes orientation toward the southeast; ore body 16 is associated with this zone. These relationships become much clearer when the geological description is considered together with Fig. 2 and the three-dimensional interpretation shown in Figs. 3 and 4. The figures help to show that the main ore bodies are not independent of the alteration system but are spatially embedded within it.

The structural interpretation of north-south, northwest-southeast and northeast-southwest fault systems is linked to the regional tectonic segmentation and magmatism of the eastern Lesser Caucasus described in earlier studies (Шихалибейли, 1966). The ophiolitic nature of the geological environment and the role of ultrabasic rocks provide an additional basis for interpreting the ore field within the metallogenic framework of the Lesser Caucasus (Гасанов, 1985; Баба-заде, 1974). The connection between quartz-carbonate and talc-carbonate alteration, fluid migration and gold-bearing sulfide mineralization is consistent with models of noble-metal ore-magmatic systems and gold-bearing sulfide fields developed for the Lesser Caucasus (Баба-заде, Абдуллаева, 2012; Баба-заде и др., 2015).

This result is significant because it shows that hydrothermal alteration and ore deposition were closely linked. The variation in alteration-zone thickness and the localization of the principal ore bodies within those zones indicate that fluid movement was structurally focused. The deposit therefore cannot be interpreted as a group of randomly distributed ore occurrences. Instead, it should be understood as a structurally guided hydrothermal system in which the major alteration corridors served as the main pathways for ore-forming fluids.

The orientation of the mineralized vein system provides additional support for this interpretation. The structural analysis indicates that most quartz-sulfide veins belong to one dominant azimuth group, whereas secondary directions are much less common. This anisotropic pattern is consistent with the geometry of the ore bodies shown in Figs. 3 and 4. The significance of this result is that the deposit preserves a preferred tectonic direction of mineralization. In geological terms, ore emplacement occurred under directed structural control, where one dominant deformation trend exerted the strongest influence on fluid migration and ore concentration.

The results also highlight the importance of host lithologies and intrusive elements. The deposit is associated with ultrabasic and gabbroic rocks, as well as rhyodacitic dikes, and these lithological units formed the setting in which hydrothermal processes developed. Certain ore bodies are directly related to dike systems, indicating that ore localization depended not only on tectonic structures, but also on lithological and intrusive conditions favorable for mineral deposition. This observation is especially important when Figs. 2 and 3 are considered together, because they show that the mineralized bodies occupy specific positions within the broader geological architecture of the deposit.

From a broader geological perspective, the results of this study show that the Soyudlu deposit may be regarded as a representative example of a structurally controlled hydrothermal gold system in the Lesser Caucasus. Its significance lies not only in the scale of mineralization, but also in the clarity with which structural control can be recognized through the combined interpretation of geological description and graphical representation. The present interpretation therefore has value beyond the deposit itself, because it illustrates an approach that may also be applied to other structurally complex gold deposits in the region. More specifically, the study shows that the combined interpretation of location schemes, ore-body maps, isometric diagrams, and directional views can provide a more convincing geological model than descriptive text alone.

The results and discussion support one consistent conclusion: ore localization at Soyudlu was governed by tectonic anisotropy, structurally focused hydrothermal circulation, and selective concentration of mineralization within a limited number of major ore bodies. The calculations presented in the previous section reinforce this interpretation numerically, while the geological figures confirm it spatially. Together, these two lines of evidence provide a coherent basis for describing the Soyudlu (Zod) deposit as a structurally controlled hydrothermal gold system.

In addition to the geological interpretation of ore-body geometry, the Surpac-based spatial model has practical significance for open-pit planning. The relationship between ore-body position, pit geometry, bench configuration and haul-road parameters allows the geological model to be linked with mine design decisions. The open-pit parameter scheme is included as an applied illustration of how the interpreted geological framework may be used during detailed exploration, boundary refinement and preliminary mine-planning stages. As shown in Fig. 5, the preliminary open-pit design parameters reflect the practical application of the geological interpretation to pit geometry, bench design, haul-road arrangement, and slope configuration.

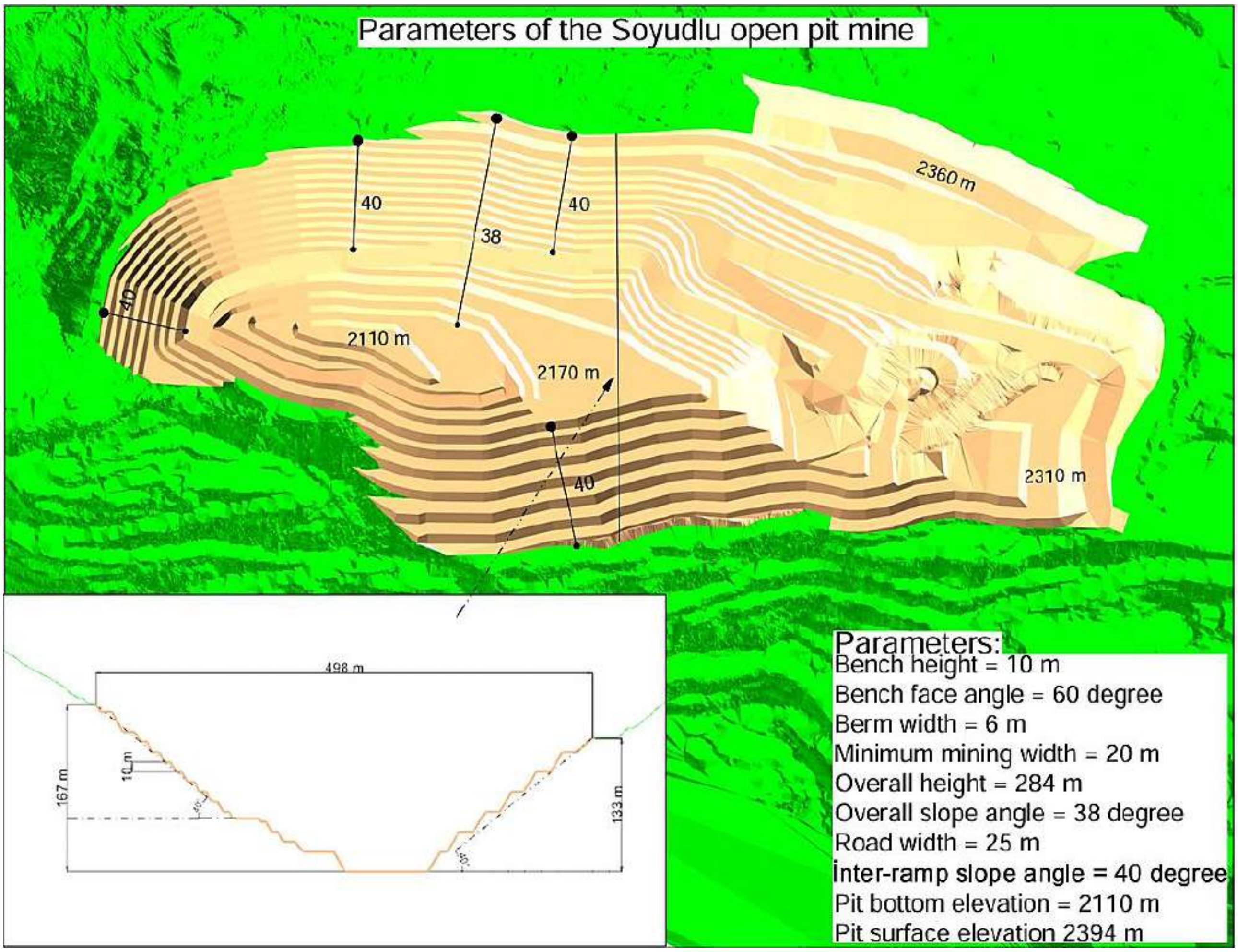

Fig. 5. Open pit design parameters of the Soyudlu (Zod) deposit

Conclusion

The geological structure and mineralization characteristics of the Soyudlu (Zod) gold deposit reveal a structurally controlled hydrothermal system. The deposit occupies a well-defined position within the Goycha-Hakari geostructural zone and the Garamanly–Zod–Soyudlu anticlinal structure. Mineralization is not uniformly distributed but is strongly focused within a limited number of principal ore bodies, specifically bodies 1, 4, 16, and 23, which account for approximately 80% of the known mineralization. This selective concentration is governed by tectonic anisotropy and structurally focused fluid migration.

The quantitative analysis of the vein system supports this interpretation, as calculations of Shannon entropy (H = 0.7306) and the normalized evenness coefficient (J = 0.665) demonstrate a high degree of structural ordering. The close spatial relationship between the major ore bodies and highly variable hydrothermal alteration zones – with thickness contrast ratios reaching 5.0 – further confirms that fluid movement was directed along specific structural corridors. Integrating three-dimensional graphical interpretations with these numerical descriptors provides a robust framework for understanding the complex architecture of the deposit. The Soyudlu deposit thus serves as a representative model for structurally focused gold mineralization in the Lesser Caucasus, and this integrated methodology can be effectively applied to similar deposits in the region.

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ГЕОЛОГИЧЕСКОЕ СТРОЕНИЕ И ОСОБЕННОСТИ МИНЕРАЛИЗАЦИИ ЗОЛОТОРУДНОГО МЕСТОРОЖДЕНИЯ СЁЮДЛЮ (ЗОД) В КАРАБАХЕ (КЕЛЬБАДЖАРСКИЙ РАЙОН)

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Резюме. Золоторудное месторождение Сёюдлю (Зод) является одним из основных золотоносных объектов Малого Кавказа. Настоящее исследование посвящено геологическому строению месторождения, пространственному распределению минерализованных тел, а также основным структурным и гидротермальным факторам, контролирующим локализацию оруденения. Особое внимание уделено графической интерпретации, поскольку геометрия рудных тел и их пространственная связь с разломными системами, дайками и зонами гидротермальных изменений представляют собой ключевую доказательную основу для понимания закономерностей минерализации. Месторождение приурочено к центральной и юго-восточной части Караманлы–Зод–Сёюдлю антиклинальной структуры в пределах Гёйча-Хакаринской геоструктурной зоны и относится к офиолитовой области Малого Кавказа. Рудное поле характеризуется габбровыми и ультраосновными породами, риодацитовыми дайками, а также сложной системой разломов север–южного, северо-запад–юго-восточного и северо-восток–юго-западного направлений. Графические материалы показывают, что минерализация сосредоточена в ограниченном числе главных рудных тел и подчинена выраженному тектоническому каркасу. Гидротермальные изменения представлены главным образом кварц-карбонатными и тальк-карбонатными ассоциациями, развитыми вдоль ранее существовавших структурных нарушений. Количественные показатели структурной упорядоченности, концентрации рудных тел и изменчивости мощностей зон изменения подтверждают интерпретацию Сёюдлю как структурно контролируемой гидротермальной золоторудной системы. Совместный анализ схемы расположения, карты распределения рудных тел, изометрической диаграммы и трехмерных видов подтверждает, что данное месторождение может рассматриваться как важная геологическая модель для понимания структурно контролируемой золоторудной минерализации Малого Кавказа.

Ключевые слова: *Сёюдлю (Зод), золоторудное месторождение, Малый Кавказ, структурный контроль, гидротермальные изменения, рудные тела, геологическая интерпретация*

QARABAĞDA YERLƏŞƏN SÖYÜDLÜ (ZOD) QIZIL YATAĞININ GEOLOJİ QURULUŞU VƏ MİNERALLAŞMA XÜSUSİYYƏTLƏRİ (KƏLBƏCƏR RAYONU)

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Xülasə. Söyüdlü (Zod) qızıl yatağı Kiçik Qafqazın əsas qızıl yataqlarından biridir. Bu tədqiqat yatağın geoloji quruluşuna, minerallaşmış cisimlərin fəzavi paylanmasına, eləcə də filizləşmənin lokallaşmasına nəzarət edən əsas struktur və hidrotermal amillərə həsr olunmuşdur. Tədqiqatda qrafik interpretasiyaya xüsusi diqqət yetirilmişdir, çünki filiz cisimlərinin həndəsəsi və onların qırılma sistemləri, dayklar və hidrotermal dəyişmə zonaları ilə fəzavi əlaqəsi minerallaşma qanunauyğunluqlarının anlaşılması üçün əsas sübut bazasını təşkil edir. Yataq Göyçə-Həkəri geostruktur zonasının Qaramanlı–Zod–Söyüdlü antiklinal strukturunun mərkəzi və cənub-şərq hissəsində yerləşir və Kiçik Qafqazın ofiolit sahəsinə aiddir. Filiz sahəsi qabbro və ultraəsasi süxurlar, riodasit daykaları, həmçinin şimal–cənub, şimal-qərb–cənub-şərq və şimal-şərq–cənub-qərb istiqamətli mürəkkəb qırılma sistemi ilə xarakterizə olunur. Qrafik materiallar göstərir ki, minerallaşma məhdud sayda əsas filiz cismində cəmlənmişdir və aydın tektonik çərçivəyə tabedir. Hidrotermal dəyişmə əsasən əvvəlcədən mövcud olmuş struktur pozulmaları boyunca inkişaf etmiş kvars-karbonat və talk-karbonat assosiasiyaları ilə təmsil olunur. Struktur nizamlılıq, filiz cisimlərinin konsentrasiyası və dəyişmə zonalarının dəyişkənliyi üzrə kəmiyyət göstəriciləri Söyüdlü yatağının struktur nəzarətli hidrotermal qızıl sistemi kimi şərhini dəstəkləyir. Yerləşmə sxemi, filiz cisimlərinin paylanma xəritəsi, izometrik diaqram və üçölçülü görünüşlərin birgə təhlili təsdiq edir ki, bu yataq Kiçik Qafqazda struktur nəzarətli qızıl minerallaşmasının anlaşılması üçün mühüm geoloji model kimi qiymətləndirilə bilər.

Açar sözlər: *Söyüdlü (Zod), qızıl yatağı, Kiçik Qafqaz, struktur nəzarət, hidrotermal dəyişmə, filiz cisimləri, geoloji interpretasiya*