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# Structural controls, mineralogy of gold-silver ores, and a proposed formation model for the Arkharly deposit (Kazakhstan)

Zamzagul Umarbekova [1], Kuanysh Togizov [2*], Geroy Zholtayev [1],
Ravil Gadeev [1], Moldir Mashrapova [1], Rustem Amanbaev [1]

[1] *K.I. Satpayev Institute of Geological Sciences, Almaty, Kazakhstan*
[2] *Satbayev University, Almaty, Kazakhstan*
**Corresponding author: e-mail k.togizov@satbayev.university*

**Abstract**

**Purpose.** To determine the role of structural-tectonic factors in the localization of gold-silver mineralization at the Arkharly deposit, characterize the mineralogical composition of the ores, and substantiate a conceptual model of deposit formation.

**Methods.** The study is based on an integrated analysis of geological exploration materials, geological maps, data on the spatial distribution of faults and orebodies, mineralogical descriptions, and published sources. The structural analysis involved comparing the orientations, morphologies, and spatial relationships of faults, quartz veins, brecciation zones, and zones of vein-disseminated mineralization. Mineralogical data were systematized with consideration of quartz generations, the composition of sulfide assemblages, the modes of occurrence of gold and silver, and hydrothermal and supergene alteration of the rocks.

**Findings.** The principal factor controlling the localization of mineralization is a system of approximately east-west- and northwest-trending oblique-slip faults with normal and strike-slip components formed under a dextral strike-slip regime. Four types of ore zones were distinguished: right- and left-stepping en echelon fracture zones, deformation and ductile shear zones, and extensional fracture zones within subvolcanic rocks. Northwest-trending right-stepping en echelon fracture zones are the most productive. Ore shoots and zones with elevated Au and Ag grades are confined to fault-intersection nodes and segments characterized by changes in vein orientation. The ores comprise several generations of quartz, pyrite, galena, sphalerite, chalcopyrite, native gold, and silver-bearing phases. The principal economic mineralization is associated with late generations of gray and dark-gray quartz. Based on the combined evidence, the deposit is provisionally classified as a low-sulfidation epithermal system. The proposed model comprises structural preparation of the ore field, early quartz formation, the principal stage of quartz-sulfide mineralization, and supergene redistribution of precious metals.

**Originality.** A conceptual model is proposed that integrates the structural evolution of the volcanic dome, the types of ore-hosting faults, orebody morphology, and the stages of mineralization. The role of repeated fault reactivation in the formation of ore shoots is demonstrated.

**Practical implications.** The obtained results can be used to predict analogous mineralization in South Junggar and other volcano-plutonic belts of Central Asia with similar geological settings. The principal exploration indicators include right-stepping en echelon fracture zones, fault-intersection nodes, brecciation zones, silicification, and hydrothermal alteration of the host rocks.

***Keywords:*** *gold-silver mineralization; Arkharly deposit; structural control; volcanic dome structure; quartz veins; ore mineralogy; low-sulfidation*

## 1. Introduction

Gold-silver deposits associated with Paleozoic and Early Mesozoic volcano-plutonic belts are of considerable interest both for understanding ore-forming processes and for predicting and assessing the potential of precious-metal mineralization. Particular importance is attached to identifying the structural factors that control hydrothermal fluid migration pathways, orebody morphology, and the localization of zones with elevated gold and silver grades [1], [2].

Epithermal gold-silver deposits predominantly form at shallow depths within volcanic and volcano-plutonic complexes as a result of the circulation and discharge of hydrothermal fluids. Depending on the composition of ore-forming fluids, the degree of sulfidation, and the nature of hydrothermal-metasomatic alteration, epithermal systems are classified into high-, intermediate-, and low-sulfidation types. Low-sulfidation deposits are commonly characterized by vein and vein-disseminated mineralization, multistage quartz formation, relatively low sulfide contents, and the development of banded, brecciated, cockade, colloform, and drusy quartz textures. The spatial distribution of ores in such systems is controlled by the combined influence of the physicochemical conditions of mineral deposition and the permeability of ore-hosting structures [3]-[5].

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Structural permeability of rocks is one of the key factors controlling the formation of epithermal mineralization. Faults and associated fracture systems act as pathways for hydrothermal fluid migration, whereas fault bends, branches, intersections, and terminations may form local zones of extension, rock fragmentation, and fluid discharge. Favorable conditions for the formation of quartz veins and ore shoots commonly develop within en echelon fracture systems, fault-intersection zones, areas of stepped fault displacement, and segments where ore-hosting structures change their orientation [6], [7]. Repeated reactivation and cyclic opening of pre-existing fractures promote brecciation of early vein aggregates, influx of new hydrothermal fluid pulses, and formation of multistage veins characterized by complex textural and mineralogical relationships [8].

South Junggar forms part of the Central Asian Orogenic Belt, which developed through accretionary-collisional processes and the evolution of the Paleo-Asian Ocean [9]-[14]. During the Late Paleozoic to Early Triassic, extensive subaerial volcanism occurred in the region, accompanied by the development of complex volcano-tectonic structures and intense post-volcanic hydrothermal activity. These conditions resulted in the formation of a series of vein and vein-disseminated gold-silver occurrences spatially associated with subvolcanic and extrusive magmatic complexes.

Gold and gold-silver deposits within the Central Asian Orogenic Belt are commonly spatially associated with Late Paleozoic and Early Mesozoic volcano-plutonic complexes, volcanic dome structures, and fault systems of various orders [15], [16]. At the same time, individual deposits differ substantially in orebody morphology, the relative proportions of vein and vein-disseminated mineralization, the composition of sulfide assemblages, the stages of quartz formation, and the intensity of supergene processes. Therefore, the identification of local structural and mineralogical patterns is necessary not only to refine the genetic model of a particular deposit but also to develop reliable exploration criteria for comparable volcano-tectonic settings.

One such occurrence is the Arkharly gold-silver deposit, which is confined to a volcanic dome structure complicated by a system of faults with different orientations and kinematics [17]. Several ore areas are distinguished within the ore field, differing in orebody morphology, quartz vein parameters, and Au/Ag ratios. These features highlight the need for an integrated analysis of the deposit's structural framework and the mineralogical characteristics of its ores.

Previous studies of the Arkharly deposit focused mainly on the mineralogical characteristics of the oxidation zone, including the modes of occurrence of silver halides [18], and on the possible role of hydrothermal eruptions in the formation of gold mineralization [19]. A more recent study interpreted the formation and geological structure of the Arkharly gold ore cluster as the result of the successive development of volcanic and magmatic processes divided into six principal stages; it also outlined the exploration potential of deeper levels and the flanks of known ore zones [20]. Recent investigations of silver halides in the oxidation zone of the Arkharly deposit compared their chemical composition with that of silver halides from several other deposits, identified iodargyrite, and discussed a possible source of iodine [21]. A review of worldwide advances in the study of silver halides was also provided [22].

Current investigations of structurally controlled deposits involve digital fracture mapping and analysis, as well as the construction of three-dimensional geographic information system models of faults, orebodies, and host rocks [23], [24]. The effectiveness of GIS-based integration of geological and geochemical data, visualization of the spatial architecture of orebodies, and delineation of prospective areas has been demonstrated for the Shok-Karagay ore field in Northern Kazakhstan [25]. Another promising approach involves using multispectral satellite data to detect and map zones of hydrothermally altered rocks, as demonstrated for the Aidarly deposit in Eastern Kazakhstan [26].

Further opportunities for spatial interpretation and the prediction of prospective areas are provided by integrating geological data with gravity survey results and satellite remote sensing [27]-[29]. However, such integrated approaches have not been presented in the available publications on the Arkharly deposit [18]-[20], and the relationships among ore-hosting structures, orebody morphology, hydrothermal alteration of the host rocks, and the mineralogical stages of ore formation remain insufficiently understood. The available information is contained in fragmented exploration reports and published sources and has not previously been integrated into a unified structural-genetic model of the deposit.

Thus, the principal unresolved issue is the absence of an integrated understanding of how the structural evolution of the Arkharly volcanic dome controlled the distribution of different ore-zone types, the morphology of quartz veins, the localization of ore shoots, and the sequence of gold-silver mineral formation. Addressing this issue requires the joint interpretation of structural-tectonic, morphological, and mineralogical data within a unified conceptual model.

This study aims to determine the role of structural-tectonic factors in the localization of gold-silver mineralization at the Arkharly deposit, characterize the mineralogical composition of the ores, and substantiate a model of deposit formation. To achieve this aim, the following objectives were addressed: analysis of the ore field's tectonic framework and the types of ore-hosting faults; characterization of orebody morphology and spatial position; synthesis of data on ore mineralogy and composition; and determination of the relationships between the deposit's structural and mineralogical characteristics.

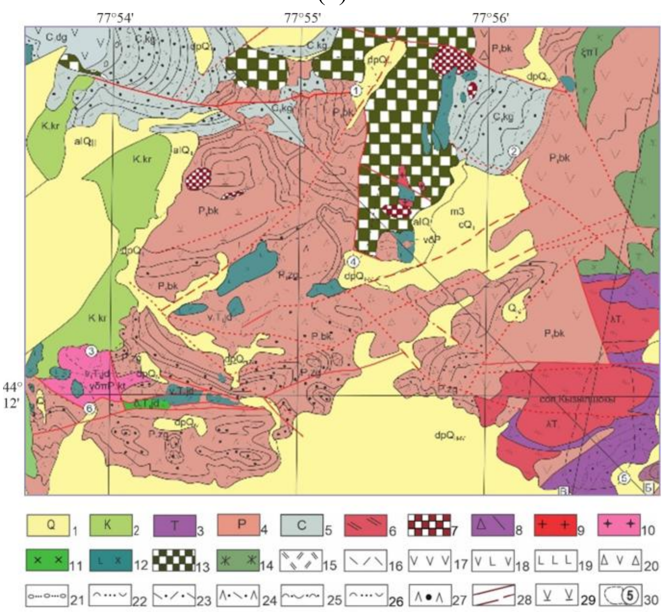
## 2. Methods

### 2.1. Study area and geological setting of the deposit

The Arkharly gold-silver deposit is located in South Junggar, within a zone of Late Paleozoic-Early Triassic volcano-plutonic magmatism, and is confined to the Arkharly volcanic dome structure (Fig. 1). Structurally, the study area belongs to the Junggar segment of the Central Asian Orogenic Belt, whose formation was associated with Paleozoic accretionary-collisional processes [1], [10], [12]-[14]. A combination of Hercynian fold-block structures and younger dome-block uplifts characterizes the geological framework of the area. The basal part of the ore-field succession consists of volcanogenic-sedimentary rocks of the Kogaly Formation ($C_2$-$P_1$), overlain by subaerial volcanic sequences of the Beskainar ($P_1$bk), Zhalgyzagash ($P_{1-2}$žg), Zheldikara ($P_2$žk), and Malaisary ($T_1$ml) formations. These units constitute a predominantly andesite-dacite volcanic succession comprising lava flows, ignimbrites, tuffs and conglomerates.

(a)


(b)




1 – Quaternary deposits;
2 – Cretaceous deposits;
3 – Triassic deposits;
4 – Permian deposits;
5 – Carboniferous deposits;
6 – Kyzylshoky volcanic necks ($\lambda T_1$);
7 – subvolcanic trachyandesite bodies (T);
8 – vent and near-vent breccias of Kyzylshoky;
9 – granite porphyries (Pkt);
10 – granodiorite porphyries ($\gamma\delta\pi P_1kt$);
11 – diorites ($\delta_2T_1jd$);
12 – gabbro-diabases ($\nu_1T_1jd$);
13 – subvolcanic trachyandesite bodies ($\delta\mu P$);
14 – syenodiorite porphyries and granodiorite porphyries ($\xi\pi T$);
15 – lavas;
16 – tuffs;
17 – andesites;
18 – basaltic andesites;
19 – basalts;
20 – andesitic clastolavas;
21 – sandstones and conglomerates;
22 – tuffaceous sandstones;
23 – rhyolitic tuffs;
24 – rhyodacitic tuffs;
25 – thin interbedding of sandstones and tuffaceous sandstones;
26 – tuffaceous sandstones with tuffite interbeds;
27 – dacitic tuffs;
28 – faults:
(a) exposed at the surface;
(b) concealed beneath Quaternary deposits;
29 – pyroxene-plagioclase basaltic andesites;
30 – ore areas:
1 – Northern;
2 – Northeastern;
3 – Eastern;
4 – Eastern II;
5 – Kyzylshoky;
6 – Central.

***Figure 1. Geological setting of the Arkharly deposit [30], [31]: (a) regional location; (b) geological map of the ore field***

Late Permian volcanic rocks of the Zheldikara Formation play the principal role in the geological structure of the ore field and host most of the identified ore zones. Andesites, basaltic andesites, tuffs, and tuffaceous conglomerates of varying grain size represent them. The succession is intruded by subvolcanic bodies of diorite porphyry forming stocks and sill-like bodies.

The Upper Paleozoic volcanic succession is unconformably overlain by unconsolidated Mesozoic-Cenozoic deposits of the Kalkan ($K_2$-$P_2kk$) and Aktau ($P_3$-$N_1ak$) formations, represented by pebble beds, gravelstones, sands, and clays. These deposits occupy topographic depressions and partly cover the flanks of the ore field.

Thus, the geological setting of the deposit is defined by its confinement to a Late Paleozoic-Early Triassic volcanic dome structure formed under conditions of active volcanism and subsequent hydrothermal activity.

### 2.2. Source geological and exploration data

This study is based on geological exploration materials obtained for the Arkharly gold-silver deposit, supplemented by an analysis of published data. The materials used included a geological map of the ore field, information on the distribution of the principal faults and ore areas, stratigraphic and lithological characteristics of the host rocks, and data on the spatial position and morphology of the orebodies.

The structural analysis considered data on the strike and dip angles of faults, quartz veins, and zones of vein-disseminated mineralization. Information on zones of rock crushing and deformation, tectonic breccias, splay fractures, and areas of increased fracture density was also examined.

The characterization of ore composition was based on available mineralogical descriptions of quartz-sulfide mineralization, information on the modes of occurrence of gold and silver, quartz generations, the composition of sulfide minerals, and hydrothermal and supergene alteration of the host rocks.

Published studies on the tectonic evolution of the Central Asian Orogenic Belt, volcanic dome structures in South Junggar, the geological framework of the Arkharly ore cluster, and the characteristics of epithermal gold-silver deposits were used to clarify the regional geological setting of the deposit and to interpret its structural and mineralogical features.

The integrated analysis of geological, structural, and mineralogical data was used to distinguish the principal types of ore-hosting structures, examine orebody morphology, and subsequently substantiate a conceptual model for the formation of the Arkharly deposit.

### 2.3. Structural analysis methodology

The study objectives included analysis of the ore field's tectonic framework and the types of ore-hosting faults, as well as characterization of the morphology and spatial distribution of the orebodies.

The structural analysis was performed by systematizing and comparing available geological and exploration data on the spatial distribution of faults, crushing zones, fractures, quartz veins, and vein-disseminated mineralization. For the principal structural elements, strike direction, dip angle and direction, extent, internal architecture, and position relative to the orebodies were considered.

The interpretation of fault structures included analysis of their orientation, inferred kinematics, and spatial relationships. Particular attention was given to approximately east-west- and northwest-trending strike-slip-normal faults, as well as associated en echelon fracture systems, deformation zones, and extensional fractures hosting quartz veins and vein-disseminated mineralization.

The relative sequence of structural development was assessed from the spatial relationships between faults and orebodies, the displacement and segmentation patterns of quartz veins, and evidence of repeated tectonic reactivation. On this basis, the faults were classified as pre-ore, syn-ore, or post-ore structures.

Ore zones were classified according to their structural position, the orientation of ore-hosting faults, quartz-vein morphology, and the presence of apophyses, splay veinlets, stockwork zones, and zones of vein-disseminated mineralization. Comparison of these characteristics allowed four principal types of ore zones to be distinguished: zones of right-stepping en echelon fractures, zones of left-stepping en echelon fractures, zones of deformation and ductile shear, and zones of extensional fractures within subvolcanic rock bodies.

The relationship between structural elements and gold-silver mineralization was evaluated by examining the spatial associations of orebodies, zones of increased vein thickness, and ore shoots with fault-intersection zones, changes in vein orientation, and areas of intense fracturing. The results were used to determine the role of faults as pathways for hydrothermal fluid migration and as structural traps controlling the localization of quartz-sulfide mineralization.

### 2.4. Methodology for mineralogical data synthesis and interpretation

The mineralogical characterization of the gold-silver ores was conducted through the systematization and comparative analysis of geological exploration materials, available mineralogical descriptions, and published data on the Arkharly deposit. The analysis included gangue and ore minerals, their modes of occurrence, the textural and structural characteristics of the ores, and the spatial relationships between mineral assemblages and the various ore zones.

Quartz generations were compared for color, grain size, aggregate morphology, and textural type. The analysis considered massive, banded, brecciated, cockade, colloform, and drusy textures, as well as the spatial relationships of different quartz generations with sulfide mineralization and precious metals. These features were used to establish the relative sequence of quartz formation and distinguish the principal stages of mineralization.

Sulfide mineralization was analyzed with consideration of its relative abundance, mineral composition, and modes of occurrence in quartz veins and zones of vein-disseminated mineralization. Disseminated, veinlet, and nest-like sulfide occurrences were compared with respect to their association with different quartz generations and their position within the identified ore-zone types.

The analysis of gold occurrence considered the size and morphology of gold particles, as well as their spatial association with quartz and sulfide minerals. The modes of silver occurrence were assessed with respect to its presence in sulfide minerals and discrete silver-bearing phases. Primary hydrothermal mineralization and secondary mineral assemblages of the oxidation zone were analyzed separately.

Hydrothermal alteration of the host rocks was classified by mineral composition, alteration intensity, and spatial association with quartz veins and ore-hosting structures. Supergene alteration was assessed based on the development of iron oxides and hydroxides, secondary forms of gold, and silver-bearing minerals in the near-surface part of the deposit.

Comparisons of quartz generations, sulfide assemblages, the modes of occurrence of gold and silver, and hydrothermal and supergene alteration were used to reconstruct the sequence of mineral formation and to evaluate the relationship between mineralogical stages and the structural evolution of the ore field.

### 2.5. Methodology for developing the conceptual model of deposit formation

The conceptual model for the formation of gold-silver mineralization at the Arkharly deposit was developed through the integrated comparison of geological, structural-tectonic, and mineralogical data. The model incorporated the geodynamic setting of the deposit, the characteristics of the volcanic dome structure, the spatial distribution of faults, orebody morphology, quartz generations, ore mineral assemblages, and the nature of hydrothermal alteration in the host rocks.

At the first stage, the sequence of development of the principal geological and structural elements of the ore field was analyzed. This included the emplacement of subvolcanic bodies, the formation of the volcanic dome structure, the development of fracture and deformation zones, and the subsequent reactivation of ore-hosting faults.

At the second stage, the role of faults and associated fractures in creating pathways for hydrothermal fluid migration and controlling the localization of quartz-sulfide mineralization was evaluated. Particular attention was given to the spatial association of orebodies with fault-intersection zones, segments characterized by changes in quartz-vein orientation, and zones of enhanced rock permeability.

At the third stage, the structural data were compared with the sequence of mineral formation. Early and late quartz generations, sulfide assemblages, modes of occurrence of gold and silver, and hydrothermal alteration of the host rocks were interpreted as indicators of successive stages of the ore-forming process.

The genetic interpretation of the deposit was based on generally accepted diagnostic characteristics of high-, intermediate-, and low-sulfidation epithermal gold-silver systems. The comparison considered the geotectonic setting, style of volcanism, structural controls on mineralization, ore and gangue mineral assemblages, quartz textures, and types of hydrothermal alteration.

The final stage involved integrating the identified structural and mineralogical patterns into a sequential scheme illustrating the preparation of ore-hosting structures, the migration of hydrothermal fluids, the formation of quartz-sulfide orebodies, and the subsequent supergene alteration of the near-surface part of the deposit. The resulting scheme was used to substantiate the classification of the Arkharly deposit as a low-sulfidation epithermal system and to formulate exploration criteria for analogous mineralization.

## 3. Results and discussion

### 3.1. Geological setting and structural framework of the Arkharly deposit

Volcanic dome structures play an important role in controlling the localization of mineralization in deposits of South Junggar [30], [32]. The structural architecture of the Arkharly ore field is defined by the development of a stratovolcano-type volcanic dome complicated by a system of faults with different orientations and kinematics. The dome structure is elongated in an approximately east-west direction and is controlled by regional tectonic stresses associated with the reactivation of the deep-seated South Junggar Fault.

The spatial distribution of the ore areas and principal faults shown in Figure 1 indicates a close relationship between gold-silver mineralization and the internal structure of the Arkharly volcanic dome. The faults not only divide the volcanic succession into individual blocks but also form zones of enhanced fracturing and permeability favorable for hydrothermal fluid migration.

Pre-ore and syn-ore oblique-slip faults with normal and strike-slip components, predominantly trending east-west and northwest, played the principal role in controlling mineralization. The key structural element is the Central Arkharly oblique-slip fault, which can be traced over a distance of up to 20 km. Within the ore field, it branches into a system of parallel dextral faults, between which zones of intense fracturing and rock brecciation developed. Branching of the principal fault zone produced a heterogeneous stress field characterized by alternating zones of localized compression and extension. The most permeable zones developed at fault bends, splays, and intersections, facilitating the influx of hydrothermal fluids and subsequent deposition of quartz-sulfide mineralization.

Dextral strike-slip deformation resulted in the formation of four principal types of ore-hosting fault structures: right- and left-stepping en echelon fracture systems, subparallel deformation zones, and a regular network of parallel fractures within subvolcanic rock bodies.

The most productive structures are northwest-trending right-stepping en echelon fracture zones containing veins that dip northeast at angles of 50-80°. These zones host laterally extensive quartz veins accompanied by numerous apophyses and systems of splay veinlets. Vein morphology ranges from relatively linear to step-like and curved bodies, reflecting their formation within a heterogeneous stress field and a pre-ore block-fault framework.

The preferential development of economic-grade mineralization within right-stepping en echelon zones indicates that the productivity of fault structures was controlled not only by their orientation but also by their capacity for repeated opening during dextral strike-slip deformation. Recurrent fracture opening facilitated successive influxes of hydrothermal fluids and the formation of multistage quartz veins.

An important element of structural control is the development of deformation zones and tectonic breccias, which are commonly accompanied by intense kaolinization, silicification, and propylitic alteration of the host rocks. Such zones host vein-disseminated mineralization and ore shoots localized at the intersections of conjugate faults.

The confinement of ore shoots to structural intersection zones indicates locally enhanced rock permeability and more intensive interaction between hydrothermal fluids and the host-rock succession. In these areas, the duration of fluid circulation, the degree of fluid discharge, and the intensity of mineral deposition may all have increased simultaneously.

Post-ore strike-slip and normal faults generally have limited displacements, ranging from a few meters to several tens of meters, and complicate the internal architecture of the veins by causing segmentation and the displacement of individual blocks. Nevertheless, these faults do not obscure the overall spatial association of mineralization with the dextral strike-slip structural system. Therefore, the present-day segmentation of individual veins partly reflects late tectonic displacement and should not be interpreted solely as a primary feature of vein formation. Reconstruction of orebody geometry should distinguish between the primary stepped morphology of the veins and superimposed post-ore block faulting. Thus, gold-silver mineralization at the Arkharly deposit is controlled by a multilevel fault system formed under a Late Hercynian dextral strike-slip tectonic regime. The faults served a dual function, acting both as pathways for ascending hydrothermal fluids and as structural traps that controlled the localization of quartz-sulfide mineralization [33]-[35].

The identified structural relationships indicate that the volcanic dome and its associated system of oblique-slip faults formed an integrated ore-controlling framework of the deposit. At the local scale, the most prospective sites are fault branching and intersection zones, northwest-trending en echelon fracture systems, and areas of intense rock brecciation.

### 3.2. Types of ore zones and morphology of ore bodies

Gold-silver mineralization at the Arkharly deposit is confined to a system of faults formed under a dextral strike-slip tectonic regime. Several individual ore areas are distinguished within the ore field, all characterized by common spatial patterns in ore zone distribution and similar orebody morphologies. Based on structural position and orebody morphology, four principal types of ore zones are distinguished within the deposit (Table 1).

***Table 1. Principal types of ore zones and their structural-mineralogical characteristics at the Arkharly deposit****

| Ore-zone type | Structural position | Orebody morphology | Principal ore minerals | Characteristic features |
|---|---|---|---|---|
| Right-stepping en echelon fracture zones | Northwest-trending oblique-slip faults with normal and strike-slip components | Laterally extensive quartz veins with complex internal architecture, apophyses, and systems of splay veinlets | Quartz, pyrite, galena, sphalerite, chalcopyrite, Au | Principal economic orebodies: extensive vein continuity |
| Left-stepping en echelon fracture zones | Conjugate faults of different orientations | Less extensive veins are characterized by local swellings and pinching | Quartz, pyrite, galena, Ag-bearing phases | Elevated silver contents and irregular mineralization |
| Deformation and ductile shear zones | Major fault zones and associated splays | Columnar orebodies and vein-disseminated mineralization | Quartz, pyrite, galena, sphalerite, Au | Ore shoots are localized at structural intersection zones |
| Extensional fracture zones | Subvolcanic rock bodies | Veins, stockworks, and dense veinlet networks | Quartz and sulfides | Development of vein-disseminated mineralization |

*Note: the mineralogical composition is provided for the principal ore assemblages; secondary minerals and products of supergene enrichment are not included in the table

The first type comprises northwest-trending right-stepping en echelon fracture zones. These structures are the most widespread and are characterized by laterally extensive quartz veins ranging in thickness from several tens of centimeters to 10-17 m. The veins dip steeply at angles of 50-80° and are commonly accompanied by apophyses and systems of splay veinlets. In plan view, they display a stepped and segmented geometry that reflects the heterogeneity of the deformation field. The considerable thickness and lateral extent of the veins, together with their complex branching patterns, indicate that right-stepping en echelon fracture zones represent the principal type of ore-hosting structure at the deposit. Their relatively high productivity was probably related to their favorable orientation within the dextral strike-slip stress field and their capacity for repeated opening during hydrothermal activity.

The second type of ore zone is associated with left-stepping en echelon fractures, which are less widely developed and contain shorter veins. Orebody morphology within these zones is more variable, comprising northeast-, approximately east-west-, and approximately north-south-trending veins characterized by irregular thickness and frequent swell-and-pinch structures. The more variable orientation and shorter extent of the veins indicate localized opening of the left-stepping en echelon fractures. Alternating vein swellings and pinches reflect the uneven distribution of deformation and permeability along the ore-hosting structures, which may have caused the heterogeneous distribution of gold and silver. Elevated silver grades recorded in individual orebodies of this type require further comparison with the stages of mineralization and the composition of silver-bearing phases.

The third type comprises subparallel deformation zones and subductile faults within which the orebodies display a linear-zonal distribution. These zones are characterized by intense tectonic reworking of the rocks and the development of kaolinization, propylitic alteration, and silicification. The orebodies commonly have a columnar geometry and are localized at intersections between splay faults and the principal structure. Their columnar morphology reflects localized mineral deposition within the most permeable segments of the fault zones. Intersections between the principal structure and subsidiary faults may have linked several hydrothermal fluid pathways, thereby creating sites of intense ore deposition. Such structural intersections are therefore particularly important for predicting the continuation of ore shoots both at depth and along strike.

The fourth type of ore zone occurs within subvolcanic rock bodies and is represented by a regular network of parallel extensional fractures. These zones host complex veins accompanied by numerous apophyses and veinlets, as well as stockwork domains of vein-disseminated mineralization. The formation of dense extensional fracture networks was probably associated with localized extension within relatively competent subvolcanic rocks. The distribution of mineralization through numerous veinlets and stockwork zones distinguishes this type from the more clearly defined linear orebodies controlled by major faults.

In terms of morphology, the orebodies are represented predominantly by quartz veins with a complex internal structure, characterized by alternating pinches and swellings, as well as branching along both strike and dip. In the vertical section, relatively straight veins prevail and maintain a consistent dip direction at depth, indicating the structural stability of the ore-hosting faults during mineralization. The contrast between the complex, stepped, and branching geometry of the veins in plan view and their relatively stable position in vertical section suggests that horizontal segmentation was controlled mainly by local heterogeneity in the stress field. At the same time, the principal ore-hosting structures maintained their dip direction at depth, providing pathways for prolonged hydrothermal fluid circulation.

An important feature of the deposit is the development of ore shoots and zones with elevated gold and silver grades, which are confined to fault-intersection zones and to segments where vein orientation changes. Supergene enrichment is widely developed in the near-surface parts of the orebodies and is expressed by elevated concentrations of secondary gold and silver.

Thus, orebody morphology at the Arkharly deposit is governed by hierarchical structural control. At the scale of the ore field, the distribution of mineralization is controlled by a system of dextral oblique-slip faults with normal and strike-slip components. In contrast, at the local scale, orebody thickness, continuity, and productivity depend on the orientation of en echelon fractures, the position of structural intersections, the intensity of rock brecciation, and variations in quartz-vein geometry. The most prospective targets for economic mineralization are right-stepping en echelon fracture zones, fault-intersection nodes, and segments characterized by local changes in vein orientation.

### 3.3. Mineralogical composition and stages of mineralization

The ores of the Arkharly deposit belong to the quartz-sulfide gold-silver type. They are characterized by a relatively simple but variable mineral composition that reflects the multistage nature of the ore-forming process. In deposits of this type, the bulk of the ore is hosted by quartz veins and zones of vein-disseminated mineralization accompanied by hydrothermally altered host rocks [35]-[37].

Quartz is the principal gangue mineral and occurs in several generations. Early quartz forms massive and banded white-to-light-gray aggregates. Later generations are gray to dark gray, fine-grained to microcrystalline, and exhibit brecciated, cockade, colloform, and drusy textures. The principal economic gold-silver mineralization is associated with these late quartz generations.

Differences in quartz color, grain size, and textural characteristics indicate repeated opening of the ore-hosting fractures and the influx of several pulses of hydrothermal fluids. Massive and banded aggregates of white and light-gray quartz record the early stage of fracture infilling, whereas gray and dark-gray quartz characterize the main productive stage of mineral formation.

The development of brecciated and cockade textures indicates alternating episodes of tectonic fragmentation and subsequent cementation of rock and vein fragments by new quartz. Colloform and fine-grained aggregates, in turn, may reflect rapid changes in the physicochemical conditions of the hydrothermal system during mineral deposition.

Sulfide mineralization is unevenly distributed and generally accounts for only 1-3 to 5% of the ore volume. The principal ore minerals are pyrite, galena, sphalerite, and chalcopyrite, whereas covellite and secondary iron hydroxides occur in smaller amounts. Sulfides occur as disseminations, veinlets, and nest-like aggregates predominantly associated with gray and dark-gray quartz. Their spatial association with these quartz varieties confirms the productive character of the late stages of quartz formation. The heterogeneous distribution of sulfides as isolated disseminations, veinlets, and nests reflects the localized flow of ore-bearing fluids through the most permeable parts of the veins and zones of tectonic fragmentation.

Gold occurs predominantly in native form and is characterized by a fine-grained to finely dispersed distribution. It is hosted both directly in quartz and in association with sulfide minerals, particularly galena and sphalerite. Gold grain sizes range from microscopic particles to fractions of a millimeter, and their morphology varies from irregular and isometric to platy. The occurrence of gold both within quartz and in association with galena and sphalerite indicates variable depositional conditions during a single productive stage. Some gold may have precipitated contemporaneously with the sulfides, whereas individual grains formed within the intergranular spaces of quartz aggregates or filled microfractures.

Silver occurs both as isomorphic impurities in sulfide minerals and as discrete silver-bearing phases, resulting in high and extremely heterogeneous Ag grades in individual orebodies. The Au/Ag ratio varies considerably throughout the deposit and is controlled by both the type of ore zone and the stage of mineralization. The different modes of silver occurrence indicate a more complex distribution pattern than that of gold. Variations in the Au/Ag ratio among individual ore zones may be related to differences in fluid composition, mineral-forming temperature, the extent of fluid-rock interaction, and the intensity of repeated tectonic reactivation.

In our interpretation, the heterogeneous distribution of gold and silver reflects the pulsed character of ore deposition and fluctuations in the physicochemical parameters of the hydrothermal fluids.

Based on the mineralogical and textural characteristics, two principal hydrothermal stages are provisionally distinguished within the deposit. The first stage was characterized predominantly by the formation of white and light-gray quartz with limited quantities of ore minerals. The second and principal productive stage involved the formation of gray and dark-gray quartz, precipitation of pyrite, galena, sphalerite, and chalcopyrite, and development of economically significant gold-silver mineralization.

The multistage architecture of the quartz veins is consistent with the established structural controls of the deposit. Repeated reactivation of the oblique-slip faults promoted the reopening of pre-existing fractures, the influx of new pulses of hydrothermal fluids, and the superimposition of later productive mineralization on early quartz aggregates. Thus, the mineralogical stages of ore formation were directly related to the development and repeated reactivation of the ore-hosting structures.

### 3.4. Hydrothermal alterations and supergene processes

The host rocks adjacent to the orebodies underwent intense hydrothermal alteration expressed by propylitic alteration, kaolinization, K-feldspar alteration, and silicification. These alteration zones range in thickness from several meters to several tens of meters and represent important exploration indicators of gold-silver mineralization.

The spatial association of altered rocks with quartz veins and ore zones indicates a genetic relationship between metasomatic processes and the circulation of hydrothermal fluids. Propylitic alteration is the most widespread and predominantly affects andesitic volcanic rocks.

The photograph shows exposed surfaces of the host rocks, represented by andesites, within the alteration zone surrounding quartz veins at the Arkharly deposit (Fig. 2). The rocks display a gray-green coloration resulting from propylitic alteration.

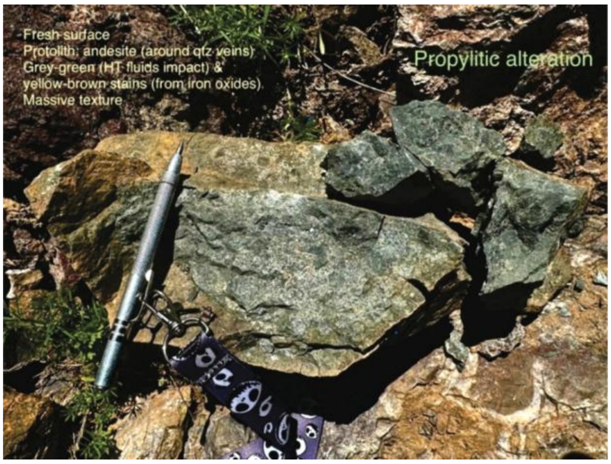



***Figure 2. Propylitically altered andesites hosting quartz veins at the Arkharly deposit***

Yellow-brown patches are also observed and are associated with iron oxides and hydroxides, indicating subsequent oxidation and supergene alteration of the rocks. Propylitic alteration is expressed by the development of secondary chlorite, epidote, and calcite, which are typical of the peripheral zones of hydrothermal systems.

The combination of propylitic alteration, its broad spatial extent, and its association with quartz veins indicates that these rocks occur within a hydrothermal alteration halo and confirms their significance as an exploration indicator.

The development of propylitic alteration along the margins of the ore zones, together with more intense silicification, kaolinization, and K-feldspar alteration near the ore-hosting structures, reflects the zoned architecture of the hydrothermal-metasomatic alteration halos. This zoning may have developed as a result of decreasing temperature and changes in fluid composition with increasing distance from the principal fluid-flow pathways.

The oxidation zone is well developed at the deposit. The photograph shows a quarry wall at the Arkharly deposit composed of intermediate to felsic volcanic rocks (Fig. 3).

The rocks are characterized by fracturing, hydrothermal alteration, and typical oxidation-zone features. This reflects hydrothermal alteration followed by subsequent weathering processes. The rocks dip eastward at an angle of about 30°.

The presence of fractures and brecciation zones facilitated the penetration of meteoric waters into the near-surface parts of the orebodies and the development of oxidation processes that affected primary sulfide minerals. As a result, iron oxides and hydroxides formed, precious metals were redistributed, and secondary mineral phases developed.

Secondary gold, associated with supergene enrichment processes, is developed in the near-surface zone (Fig. 4).

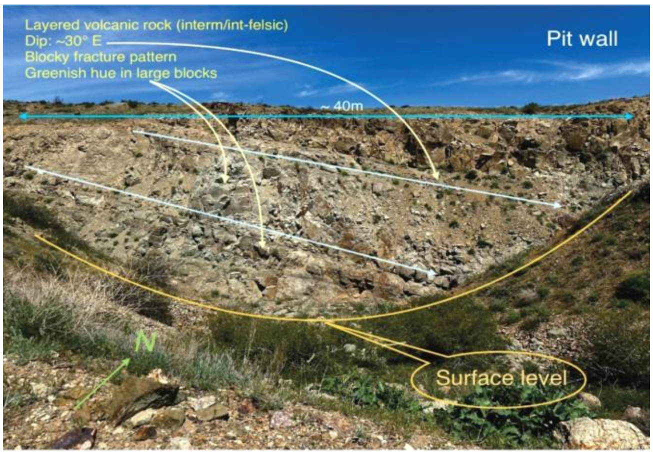



***Figure 3. Exposure of volcanic rocks and structural elements of the oxidation zone at the Arkharly deposit***

Fine- and colloform-dispersed gold particles, as well as dendritic forms, indicate the mobilization and redeposition of gold under oxidation-zone conditions. The formation of Liesegang rings reflects periodic precipitation of gold from migrating solutions in response to changing geochemical conditions.

Silver occurs both as isomorphic impurities in sulfides and as discrete silver-bearing phases. Various silver halides have been identified in the deposit's oxidation zone [18].

The development of secondary silver-bearing minerals indicates the redistribution of silver during the destruction of primary sulfides. Owing to the different mobility of gold and silver under supergene conditions, their original ratio may have changed significantly in the near-surface parts of the orebodies. Therefore, high precious-metal contents in the oxidation zone do not always directly reflect the composition of the primary hydrothermal mineralization.

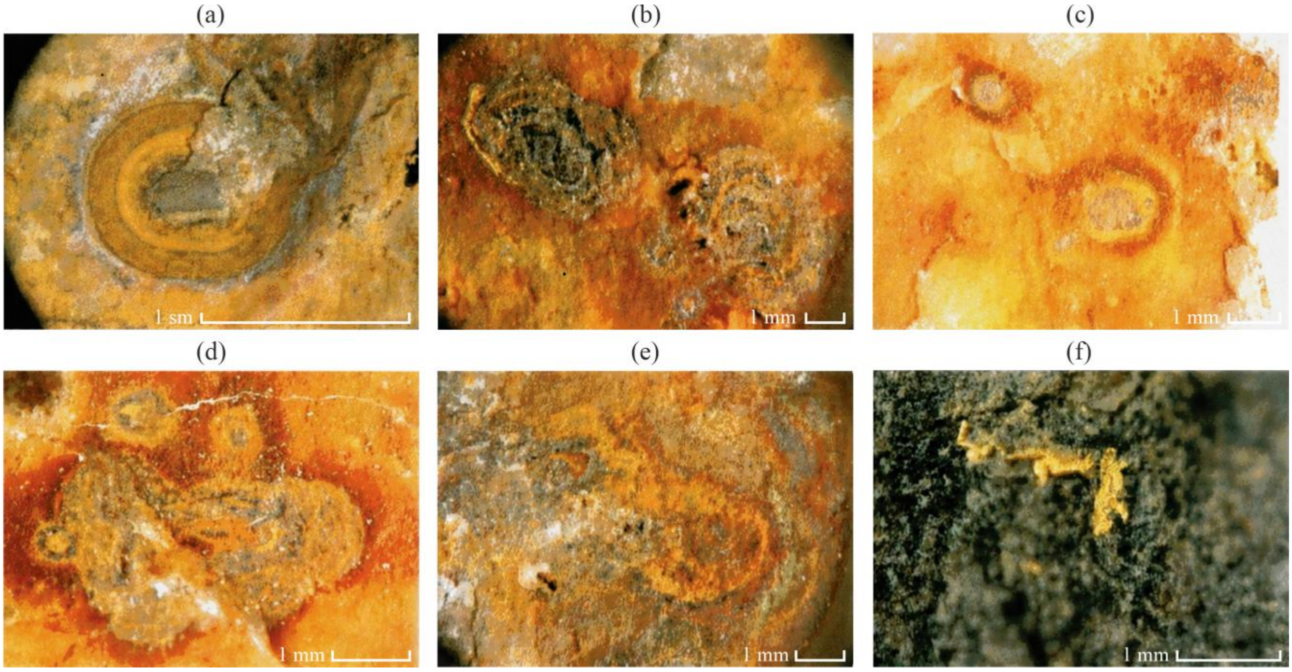



***Figure 4. Fine-dispersed and dendritic gold in the oxidation zone of the Arkharly deposit: (a)-(e) fine- and colloform-dispersed supergene gold formed in the oxidation zone as Liesegang rings; (f) dendritic supergene gold, after [38]***

Thus, the present-day mineralogical structure of the near-surface part of the deposit was formed through the superposition of two successive processes. The primary stage was associated with hydrothermal alteration of the volcanic rocks and the formation of propylitic, kaolinitic, K-feldspar, and silicified halos. The later stage included sulfide oxidation, the formation of iron oxides and hydroxides, and the mobilization and redeposition of gold and silver. From a practical perspective, the most informative exploration indicators are the spatial association of quartz veins, propylitized and kaolinized rocks, zones of intense fracturing, ferruginous oxidation products, and secondary forms of gold and silver.

### 3.5. Deposit classification and proposed formation model

According to the widely accepted classification, epithermal deposits are subdivided into high-, intermediate-, and low-sulfidation types [36], [37], [39]. The Arkharly epithermal gold-silver deposit is classified as a low-sulfidation system.

This classification is based on a combination of geological, structural, and mineralogical characteristics. These include the confinement of mineralization to a volcanic dome structure, the predominance of vein and vein-disseminated mineralization, multistage quartz formation, relatively low sulfide contents, the presence of colloform, cockade, and brecciated textures, and the development of propylitic and argillic alteration in the host rocks. Nevertheless, this classification is based primarily on geological and mineralogical evidence. Its definitive confirmation will require further data on the chemical composition of ore minerals, fluid inclusions, the temperature and salinity of mineral-forming fluids, and stable isotope compositions.

The proposed model is consistent with established concepts of the formation of low-sulfidation epithermal deposits, which are controlled by volcano-tectonic structures [37] (Fig. 5). The presented scheme is used as a general genetic model for low-sulfidation epithermal systems. Its applicability to the Arkharly deposit is considered based on similarities in structural control, the vein and vein-disseminated character of mineralization, multistage quartz formation, and relatively low sulfide contents.

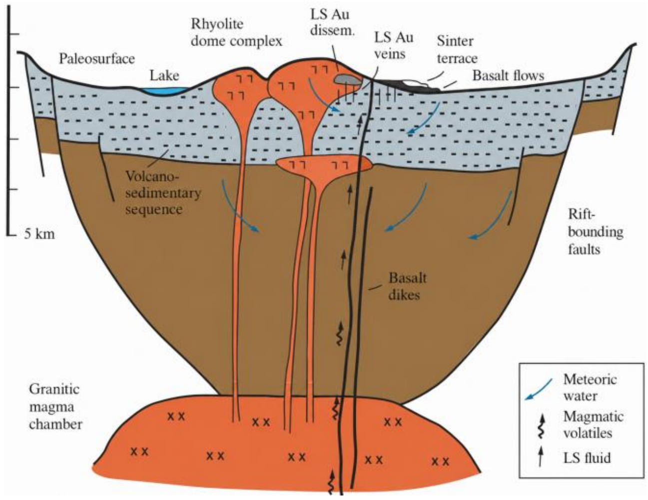



***Figure 5. General conceptual model for the formation of low-sulfidation epithermal gold-silver mineralization, modified from [37], [40]-[42]***

At the same time, the rift-related geodynamic setting, the bimodal nature of magmatism, and the mechanism of deep-seated neutralization of magmatic fluids at the Arkharly deposit require independent substantiation.

The combined geological, structural, and mineralogical evidence indicates that the gold-silver mineralization at the Arkharly deposit formed under an active Late Paleozoic – Early Triassic volcano-tectonic regime. Ore formation was primarily controlled by the development of a volcanic dome structure complicated by a system of oblique-slip faults with normal and strike-slip components, which governed both magmatic activity and the circulation of hydrothermal fluids.

Orebody formation proceeded through several stages. During the early stage, associated with the emplacement of subvolcanic bodies and extrusive rocks, systems of extensional fractures and deformation zones developed, enhancing rock permeability. These structures served as the principal pathways for ascending fluids and established the framework of the subsequent ore-hosting zones.

The initial stage is the stage of structural preparation of the ore field. Magmatic emplacement, dome formation, and the development of dextral strike-slip deformation resulted in a network of oblique-slip faults, en echelon fractures, brecciation zones, and extensional fractures. Their opening created pathways for the subsequent migration of hydrothermal fluid.

The main stage of ore formation was associated with post-volcanic hydrothermal activity. During this period, quartz and sulfide minerals precipitated, forming quartz-sulfide veins and zones of vein-disseminated mineralization. Heterogeneous stress conditions and repeated fault reactivation produced the complex vein morphology, stepped geometry, numerous apophyses, and ore shoots localized at fault-intersection zones.

The early hydrothermal stage was characterized predominantly by the deposition of white and light-gray quartz containing relatively few ore minerals. Subsequent reactivation of the fault structures resulted in the reopening of fractures, brecciation of early quartz, and the influx of new pulses of ore-bearing hydrothermal fluids.

The mineralogical characteristics of the ores indicate a multistage hydrothermal process. Early quartz generations containing limited ore mineralization were succeeded by later gray and dark-gray varieties associated with the principal gold-silver mineralization. The heterogeneous distribution of sulfides and sharp variations in Au and Ag grades reflect the pulsed character of ore deposition and localized changes in the physicochemical parameters of the hydrothermal fluids.

The main productive stage was characterized by the formation of gray and dark-gray quartz, precipitation of pyrite, galena, sphalerite, and chalcopyrite, and deposition of native gold and silver-bearing phases. Variations in temperature, pressure, acidity, redox conditions, and fluid composition may have led to spatially heterogeneous precipitation of gold and silver.

Tectonic controls played a major role in the formation of economically significant concentrations of precious metals. Ore shoots and zones of elevated grades are associated with changes in vein attitude, fault intersections, and areas of intense fracturing.

The most favorable conditions for ore deposition developed at fault branches, bends, and intersections, where fracture-space volume increased sharply, and fluid pressure decreased. The discharge of hydrothermal fluids within these structural nodes promoted the formation of ore shoots and localized zones of increased quartz-vein thickness.

In the near-surface zone, additional ore enrichment was associated with supergene processes that formed secondary gold and silver. Following the hydrothermal stage, the primary quartz-sulfide ores underwent oxidation. Sulfide breakdown, migration of metal-bearing solutions, and redeposition of precious metals resulted in the formation of finely dispersed, colloidal, and dendritic gold, as well as secondary silver-bearing minerals.

Overall, the combined characteristics of the Arkharly deposit indicate that it represents a gold-silver system formed within a volcanic dome setting, with ore distribution predominantly controlled by structural factors. This model is consistent with other gold-silver deposits associated with volcano-plutonic belts of Central Asia and may be applied to the exploration of analogous deposits in South Junggar.

The proposed model comprises four successive stages:

1) formation of the volcanic dome structure and structural preparation of the ore field;

2) early quartz formation;

3) the principal stage of quartz-sulfide gold-silver deposition associated with repeated fault reactivation;

4) supergene alteration and secondary redistribution of gold and silver.

From an exploration perspective, the most prospective targets for analogous mineralization are intersections of dextral faults, northwest-trending right-stepping en echelon fracture zones, tectonic breccias, areas of intense silicification and propylitic alteration, and near-surface zones containing ferruginous oxidation products and secondary forms of precious metals.

Further testing of the identified exploration criteria may involve constructing a three-dimensional geological model of the deposit and comparing the spatial distribution of orebodies with the inferred thermodynamic conditions of mineral formation. The effectiveness of combining three-dimensional models with thermodynamic data in delineating and assessing prospective areas has previously been demonstrated for other ore deposits in Kazakhstan [43].

## 4. Conclusions

The Arkharly gold-silver deposit formed within a Late Paleozoic-Early Triassic volcanic dome structure associated with subaerial volcanism and post-volcanic hydrothermal activity. A system of approximately east-west primarily controls ore distribution, and northwest-trending oblique-slip faults with normal and strike-slip components, which host quartz veins, zones of vein-disseminated mineralization, and magmatic breccias.

Four principal types of ore zones are distinguished within the deposit, differing in orebody morphology and the intensity of tectonic reworking of the host rocks, with right-stepping en echelon fracture zones playing the dominant role. The ores belong to the quartz-sulfide gold-silver type and are characterized by multistage mineralization. The principal economic mineralization is associated with late generations of gray and dark-gray quartz that contain pyrite, galena, sphalerite, chalcopyrite, and native gold. The localization of ore shoots and zones with elevated Au and Ag grades is controlled by structural nodes, particularly fault-intersection zones and segments characterized by changes in vein attitude.

Based on the combined geological, structural, and mineralogical characteristics, the Arkharly deposit is provisionally classified as a low-sulfidation epithermal gold-silver system. This interpretation is supported by the vein and vein-disseminated character of the mineralization, multistage quartz formation, relatively low sulfide contents, and the development of propylitic and argillaceous alteration in the host rocks.

The proposed conceptual model emphasizes the leading role of structural-tectonic factors and repeated reactivation of ore-hosting faults. The most prospective exploration indicators include northwest-trending, right-stepping, en echelon fracture zones; fault-intersection nodes; and zones of intense rock brecciation, silicification, and hydrothermal alteration. The established relationships may provide a basis for predicting analogous gold-silver deposits within the volcano-plutonic belts of South Junggar.

## Author contributions

Conceptualization: ZU, KT; Data curation: GZ; Formal analysis: MM; Funding acquisition: GZ; Investigation: ZU, RG; Methodology: KT; Project administration: ZU; Resources: ZU, RG; Software: ZU, MM, RA; Supervision: RG; Validation: ZU, KT; Visualization: MM; Writing – original draft: ZU, KT, RG; Writing – review & editing: ZU, GZ, MM. All authors have read and agreed to the published version of the manuscript.

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## Conflicts of interest

The authors declare no conflict of interest.

## Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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## Структурні чинники, мінералогія золото-срібних руд і запропонована модель формування родовища Архарли (Казахстан)

З. Умарбекова, К. Тогізов, Г. Жолтаєв, Р. Гадєєв, М. Машрапова, Р. Аманбаєв

**Мета.** Встановлення ролі структурно-тектонічних чинників у локалізації золото-срібного зруденіння родовища Архарли, характеристика мінералогічного складу руд та обґрунтування концептуальної моделі його формування.

**Методика.** Дослідження ґрунтується на комплексному аналізі матеріалів геологорозвідувальних робіт, геологічних карт, даних про просторове положення розривних порушень і рудних тіл, а також мінералогічних описів і опублікованих матеріалів. Структурний аналіз передбачав зіставлення орієнтування, морфології та просторових взаємовідношень розломів, кварцових жил, зон дроблення і прожилково-вкрапленої мінералізації. Мінералогічні дані систематизували з урахуванням генерацій кварцу, складу сульфідної асоціації, форм знаходження золота й срібла, а також гідротермальних і гіпергенних змін порід.

**Результати.** Основним чинником локалізації зруденіння є система скидозсувних розломів субширотного та північно-західного простягання, сформованих в умовах правозсувного тектонічного режиму. Виділено чотири типи рудних зон: зони правих і лівих кулісних тріщин, зони зминання та в'язких розривів, а також зони тріщин відриву в субвулканічних породах. Найбільш продуктивними є зони правих кулісних тріщин північно-західного простягання. Рудні стовпи та ділянки підвищених вмістів Au і Ag, приурочені до вузлів зчленування розривних порушень і ділянок зміни орієнтування жил. Руди представлені кварцом кількох генерацій, піритом, галенітом, сфалеритом, халькопіритом, самородним золотом і срібловмісними фазами. Основне промислове зруденіння пов'язане з пізніми генераціями сірого та темно-сірого кварцу. За сукупністю ознак родовище попередньо віднесено до епітермальних систем низькосульфідизаційного типу. Запропонована модель охоплює структурну підготовку рудного поля, раннє кварцоутворення, основний етап кварц-сульфідної мінералізації та гіпергенний перерозподіл благородних металів.

**Наукова новизна.** Запропоновано концептуальну модель, що поєднує структурну еволюцію вулкано-купольної споруди, типи рудовмісних розривних порушень, морфологію рудних тіл і стадійність мінералізації. Встановлено роль повторної активізації розломів у формуванні рудних стовпів.

**Практична значимість.** Отримані результати можуть бути використані для прогнозування аналогічного зруденіння в Південній Жонгарії та інших вулканоплутонічних поясах Центральної Азії зі схожою геологічною будовою. Основними пошуковими ознаками є зони правих кулісних тріщин, вузли зчленування розломів, ділянки дроблення, окварцювання та гідротермальної зміни порід.

***Ключові слова:*** *золото-срібне зруденіння; родовище Архарли; структурний контроль; вулкано-купольна структура; кварцові жили; мінералогія руд; низькосульфідизаційний тип*

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