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MINERALOGY AND VERTICAL ZONING OF GOLD MINERALIZATION AT THE BALAZHAL DEPOSIT, EAST KAZAKHSTAN

ШЫҒЫС ҚАЗАҚСТАНДАҒЫ БАЛАЖАЛ КЕН ОРНЫ АЛТЫН КЕНДЕНУІНІҢ МИНЕРАЛОГИЯСЫ ЖӘНЕ ТІК ЗОНАЛЫЛЫҒЫ

МИНЕРАЛОГИЯ И ВЕРТИКАЛЬНАЯ ЗОНАЛЬНОСТЬ ЗОЛОТОГО ОРУДЕНЕНИЯ БАЛАДЖАЛЬСКОГО МЕСТОРОЖДЕНИЯ, ВОСТОЧНЫЙ КАЗАХСТАН

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beresitization,
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native gold,
vertical zoning.

ABSTRACT

The Balazhal gold deposit is located in the West Kalba gold belt of Eastern Kazakhstan and is hosted mainly by a differentiated gabbro-diorite-diorite intrusion. This study examines the relationships between hydrothermal alteration, ore mineralogy, native gold occurrence, and the structural position of mineralization. The study is based on geological observations, petrographic and ore microscopy, and SEM-EDS investigations. Two main styles of gold mineralization are distinguished: quartz-vein mineralization and veinlet-disseminated gold-sulfide mineralization hosted by beresitized intrusive rocks. Pyrite and arsenopyrite are the dominant sulfide minerals. Fine-grained gold is mainly associated with pyrite and arsenopyrite in beresitized rocks, whereas coarser native gold occurs predominantly in quartz veins and late quartz-carbonate assemblages. Four successive hydrothermal stages are recognized, from early beresitic alteration and pyrite-arsenopyrite mineralization to quartz-polymetallic and late quartz-carbonate mineralization. The distribution of the ore types also changes with structural level: quartz veins predominate in the upper part of the deposit, whereas broader zones of veinlet-disseminated pyrite-arsenopyrite mineralization become more important at depth. These features should be considered in exploration of the deeper parts of the Balazhal deposit.

Түйінді сөздер:

Балажал,
Батыс Қалба,
алтын кенденуі,
березиттену,

ТҮЙІНДЕМЕ

Балажал алтын кен орны Шығыс Қазақстандағы Батыс Қалба алтынды белдеуі шегінде орналасқан және негізінен дифференциацияланған габбро-диорит-диорит интрузивімен байланысты. Осы зерттеуде таужыныстардың гидротермалдық өзгерістері, кендердің минерало-



арсенопирит,
саф алтын,
тік зоналылық.

гиялық құрамы, саф алтынның кездесу формалары және кенденудің құрылымдық позициясы арасындағы өзара байланыстар қарастырылады. Зерттеу геологиялық бақылауларға, петрографиялық және минераграфиялық зерттеулерге, сондай-ақ SEM-EDS әдісімен жүргізілген зерттеулерге негізделген.

Алтын кенденуінің екі негізгі типі ажыратылды: кварц-желілі және березиттенген интрузивтік таужыныстарда локализацияланған желіше-сеппелі алтын-сульфидті кендену. Негізгі сульфидті минералдар – пирит пен арсенопирит. Березиттенген таужыныстардағы ұсақ түйірлі алтын негізінен пирит және арсенопиритпен ассоциацияда кездеседі, ал ірірек саф алтын көбінесе кварц желілеріне және кейінгі кварц-карбонатты минералдық ассоциацияларға тән.

Гидротермалдық минерал түзілуінің бірізді төрт сатысы анықталды: ерте березиттену мен пирит-арсенопиритті минералданудан кварц-полиметалды және кейінгі кварц-карбонатты минералдануға дейін. Кендену типтерінің таралуы құрылымдық деңгейге байланысты да өзгереді: кен орнының жоғарғы бөлігінде кварц желілері басым болса, тереңдеген сайын қалыңдығы жоғары желіше-сеппелі пирит-арсенопиритті минералдану аймақтарының рөлі артады. Бұл ерекшеліктер Балажал кен орнының терең горизонттарында іздеу-барлау жұмыстарын жүргізу кезінде ескерілуі тиіс.

Ключевые слова:

Баладжал,
Западная Калба,
золотое оруденение,
березитизация,
арсенопирит,
самородное золото,
вертикальная
зональность.

АННОТАЦИЯ

Баладжальское золоторудное месторождение расположено в пределах Западно-Калбинского золоторудного пояса Восточного Казахстана и приурочено преимущественно к дифференцированному габбро-диорит-диоритовому интрузиву. В настоящем исследовании рассматриваются взаимосвязи между гидротермальными изменениями пород, минералогией руд, формами нахождения самородного золота и структурной позицией оруденения. Исследование основано на геологических наблюдениях, петрографическом и минераграфическом изучении, а также исследованиях методом SEM-EDS.

Выделены два основных типа золотого оруденения: кварцево-жилльное и прожилково-вкрапленное золото-сульфидное, локализованное в березитизированных интрузивных породах. Основными сульфидными минералами являются пирит и арсенопирит. Тонкозернистое золото в березитизированных породах преимущественно ассоциирует с пиритом и арсенопиритом, тогда как более крупное самородное золото характерно главным образом для кварцевых жил и поздних кварц-карбонатных ассоциаций.

Установлены четыре последовательные стадии гидротермального минералообразования — от ранней березитизации и пирит-арсенопиритовой минерализации до кварц-полиметаллической и поздней кварц-карбонатной минерализации. Распределение типов оруденения также изменяется в зависимости от структурного уровня: в верхней части месторождения преобладают кварцевые жилы, тогда как с глубиной возрастает роль более мощных зон прожилково-вкрапленной пирит-арсенопиритовой минерализации. Эти особенности следует учитывать при проведении поисково-разведочных работ на глубоких горизонтах Баладжальского месторождения.

1. INTRODUCTION

Gold deposits hosted by structurally controlled hydrothermal systems represent an important component of the global gold resource base. Their formation commonly reflects the interaction of regional- to deposit-scale deformation, fluid migration through permeable fault and fracture networks, hydrothermal alteration of host rocks, and successive stages of sulfide and gold deposition (D'yachkov et al., 2021, 2022; Soloviev et al., 2020). Understanding the relationships among these processes is particularly important in deposits where several styles of mineralization occur within a single hydrothermal system. In such settings, the spatial distribution of alteration assemblages, sulfide minerals, quartz veins, and native gold can provide important constraints on ore localization and can be used to identify prospective extensions of known mineralized zones (D'yachkov et al., 2022; Soloviev et al., 2020).

Hydrothermal alteration is one of the principal features accompanying structurally controlled gold mineralization. In granitoid and intermediate to mafic intrusive rocks, quartz-carbonate-sericite alteration accompanied by sulfide mineralization is commonly expressed as beresitization. The development of beresite alteration zones may substantially modify the primary mineralogical composition of the host rocks and create broad envelopes around quartz veins and veinlet-disseminated mineralization (D'yachkov et al., 2022; Greku et al., 2024). Pyrite and arsenopyrite are particularly important components of many such systems because they may host fine-grained or submicroscopic gold (Filimonova et al., 2020; Kovalev et al., 2011; Stepanov et al., 2021; Sugiono et al., 2025), whereas later quartz and carbonate veins may contain coarser free native gold (Greku et al., 2024, 2025). Establishing the temporal and spatial relationships between alteration, sulfide formation, and native gold deposition is therefore essential for understanding the architecture of these mineralized systems.

Eastern Kazakhstan contains several major gold-bearing zones formed during the Paleozoic tectono-magmatic evolution of the Central Asian Orogenic Belt (D'yachkov et al., 2021, 2022; Soloviev et al., 2020). Among them, the West Kalba gold belt is one of the most important gold-producing regions of Kazakhstan and hosts numerous quartz-vein, veinlet-disseminated, and hydrothermally altered-rock-hosted gold occurrences (D'yachkov et al., 2022; Mizernaya et al., 2019; Soloviev et al., 2020). Gold mineralization within the belt is spatially associated with major fault systems, subsidiary fracture networks, intrusive bodies, and zones of hydrothermal alteration (D'yachkov et al., 2021, 2022; Kalinin et al., 2016; Soloviev et al., 2020). Despite the long history of exploration and mining in the region, the relationships between structural controls, alteration processes, ore mineral assemblages, and different styles of gold mineralization remain insufficiently constrained for a number of individual deposits.

The Balazhal deposit is located within the West Kalba gold belt and represents an example of a hydrothermal gold system combining quartz-vein and veinlet-disseminated mineralization (D'yachkov et al., 2021; Mizernaya et al., 2019). Mineralization is spatially associated with a gabbro-diorite intrusion and hydrothermally altered rocks, particularly beresites (D'yachkov et al., 2021; Mizernaya et al., 2019). Two principal styles of gold mineralization are recognized: quartz-vein mineralization occurring both within and outside the intrusive body, and disseminated to veinlet-disseminated gold-sulfide mineralization developed mainly within hydrothermally altered gabbro-diorites (D'yachkov et al., 2021; Mizernaya et al., 2019). The deposit contains numerous gold-bearing quartz veins surrounded by zones of disseminated sulfide mineralization and beresitic alteration. Previous investigations indicate that pyrite and arsenopyrite are important sulfide minerals associated with fine-grained gold, whereas free native gold occurs mainly within quartz-bearing assemblages (D'yachkov et al., 2021).

An important feature of the Balazhal system is the apparent spatial variation in mineralization styles. Quartz-sulfide veins dominate the upper structural levels, disseminated gold-sulfide mineralization associated with beresitic alteration occurs at intermediate levels,

whereas quartz–carbonate mineralization has been described in the deeper, structurally controlled parts of the system (D'yachkov et al., 2021). These relationships suggest that the different ore styles may represent vertically and temporally related components of a single hydrothermal system rather than independent mineralization events. However, the relationships among host-rock alteration, sulfide mineralization, native gold occurrence, and structural position have not yet been integrated into a unified mineralogical and structural model for the deposit.

This study therefore aims to characterize the principal styles of gold mineralization at the Balazhal deposit and to evaluate their relationships with host-rock alteration and structural controls. Particular attention is given to (1) the mineralogical characteristics of the quartz-vein and veinlet–disseminated ores, (2) the occurrence and morphology of native gold and its association with sulfide minerals, (3) the sequence of hydrothermal alteration and ore formation, and (4) the spatial distribution and vertical zoning of the principal mineralization styles. The resulting mineralogical and structural framework is used to refine the model of gold localization at Balazhal and to assess its implications for exploration within the deposit and the broader West Kalba gold belt.

2. MATERIALS AND METHODS

The study is based on the integration of geological and structural observations, previously available geological and exploration data, and petrographic and mineralogical investigations of representative rock and ore samples from the Balazhal gold deposit. Geological maps, cross-sections, exploration data, and archival materials were analyzed to characterize the geological structure of the deposit, the morphology and distribution of mineralized zones, and the spatial relationships between intrusive rocks, hydrothermal alteration, structural features, and gold mineralization.

Rock and ore samples were selected to represent the principal host rocks, hydrothermally altered rocks, quartz veins, and veinlet–disseminated gold-bearing ores. Thin and polished sections were prepared from representative samples for petrographic and ore-mineralogical investigations.

All laboratory and analytical investigations were carried out at D. Serikbayev East Kazakhstan Technical University (EKTU), Ust-Kamenogorsk, Kazakhstan. Petrographic observations of host and hydrothermally altered rocks were performed using a MICROS MC-20 optical microscope. The observations focused on primary mineral assemblages, hydrothermal alteration minerals, replacement textures, and the relationships between alteration and mineralization. Ore-mineralogical investigations of polished sections were conducted using a POLAM R-312 reflected-light microscope, with particular attention to sulfide mineral assemblages, their textural relationships, and the occurrence and morphology of native gold.

The mineral composition and microtextural relationships of the ores and hydrothermally altered rocks were additionally investigated by scanning electron microscopy (SEM) using a JEOL JSM-6390LV scanning electron microscope equipped with an Oxford Instruments INCA energy-dispersive X-ray spectroscopy (EDS) system. Backscattered-electron imaging and semi-quantitative EDS analyses were used to identify ore and gangue minerals, characterize their morphology and intergrowth relationships, and examine the occurrence of native gold and its spatial associations with sulfide minerals, particularly pyrite and arsenopyrite.

The results of optical and scanning electron microscopy were integrated with geological and structural data to distinguish the principal styles of mineralization and hydrothermal alteration. The relative sequence of alteration and ore formation was reconstructed from mineral assemblages, replacement and cross-cutting relationships, and ore textures. Particular emphasis was placed on the relationships among beresitic alteration, sulfide mineralization, quartz veining,

and native gold occurrence. The combined dataset was subsequently used to evaluate the spatial distribution of quartz-vein and veinlet-disseminated mineralization and to constrain the vertical zoning of the Balazhal hydrothermal gold system.

3. GEOLOGICAL SETTING

3.1. Regional Geological Setting

The Balazhal gold deposit is located in the southwestern part of the West Kalba gold belt of Eastern Kazakhstan, within the Kedey–Balazhal gold-bearing zone (D'yachkov et al., 2021, 2022; Kalinin et al., 2016; Kovalev et al., 2011). The ore field occurs near the junction between the Char–Gornostai ophiolite belt and the Kalba structural domain and is spatially associated with a major NW-trending fault system (D'yachkov et al., 2021; Kalinin et al., 2016; Kovalev et al., 2011). The regional geological architecture comprises strongly deformed Paleozoic volcano-sedimentary and terrigenous successions intruded by several generations of mafic to felsic magmatic rocks (D'yachkov et al., 2021; Kalinin et al., 2016).

The sedimentary succession in the Balazhal area includes the Visean Arkalyk Formation, composed of volcano-sedimentary and terrigenous rocks (Kalinin et al., 2016; Kovalev et al., 2009). Its lower part is dominated by quartz–feldspar tuffaceous and polymictic sandstones, whereas the middle part consists mainly of rhythmically interbedded sandstone and siltstone with siliceous and jasper-like horizons; the upper part is dominated by finer-grained, shale-rich rocks (Kalinin et al., 2016; Kovalev et al., 2009). These rocks are strongly deformed and affected by flexural folding.

The deformation produced fracture systems that subsequently acted as zones of enhanced permeability for intrusive emplacement and hydrothermal fluid migration. Fault systems played a major role in controlling the distribution of intrusive rocks, hydrothermal alteration, and gold mineralization throughout the district (D'yachkov et al., 2021, 2022; Kovalev et al., 2011; Soloviev et al., 2020). Faults of NW, NE, and approximately E–W orientation are recognized, with the NW-trending Char–Gornostai fault system representing the dominant regional structure (Kalinin et al., 2016; Kovalev et al., 2009).

3.2. Geology and Structural Controls of the Balazhal Deposit

The Balazhal deposit is spatially associated with a differentiated mafic to intermediate intrusive body dominated by diorite and gabbro-diorite (Kalinin et al., 2016; Kovalev et al., 2009). The intrusion has an approximately oval surface expression of about 500 × 400 m. Its internal structure is compositionally zoned: quartz diorites occur predominantly in the central part, diorites and gabbro-diorites occupy intermediate portions, and diabase and gabbro-diabase are developed mainly along the margins. The surrounding volcano-sedimentary rocks are hornfelsed within an exocontact aureole reaching approximately 200–250 m in width (Kovalev et al., 2009).

The intrusive body is closely associated with the major fault system and is interpreted as a structurally controlled intrusion. In its southwestern and deeper parts, the intrusion is bounded by the Char–Gornostai fault. Three principal fault and fracture systems are recognized within the deposit (Figure 1). The NW-trending system includes the major Char–Gornostai structure and parallel subsidiary faults. NE-trending fractures host numerous gold-bearing quartz veins and linear zones of beresitic alteration containing disseminated gold–sulfide mineralization. Approximately E–W structures locally control individual quartz veins (Kalinin et al., 2016; Kovalev et al., 2009).

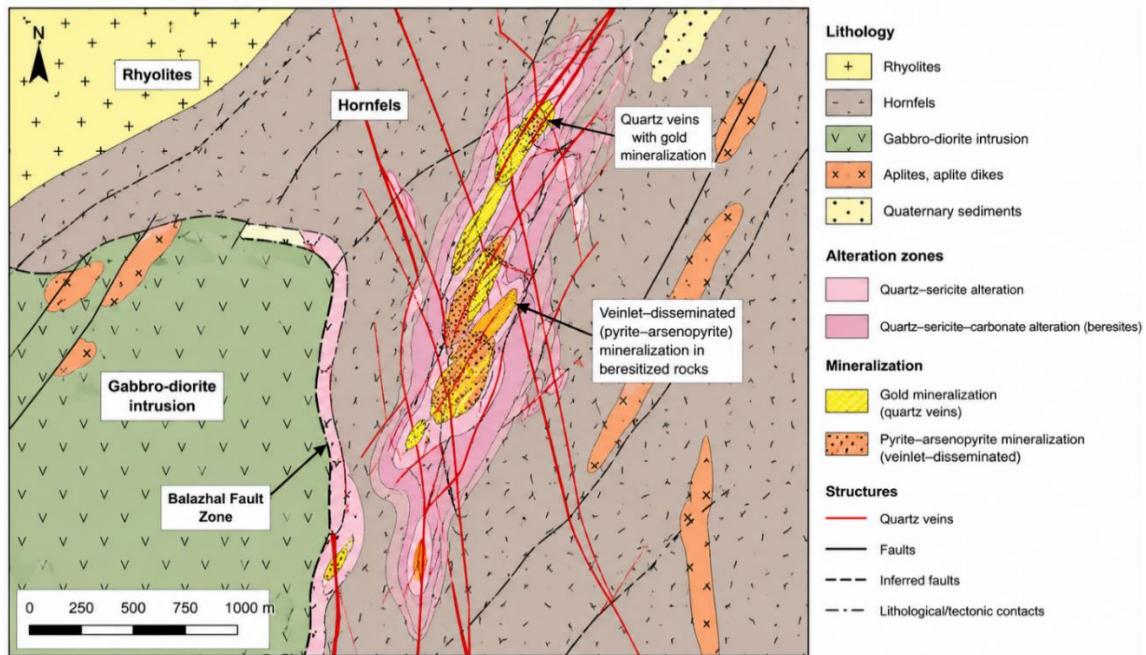


Figure 1. Geological and structural scheme of the Balazhal gold deposit, showing the spatial relationships among the gabbro-diorite intrusion, fault and fracture systems, hydrothermal alteration zones, gold-bearing quartz veins, and veinlet-disseminated pyrite-arsenopyrite mineralization. Redrawn and simplified from the original geological materials of the Balazhal deposit

Note – Prepared by the authors based on (Kalinin K.R., 2011)

Hydrothermal alteration is widespread within and around the intrusive body. Beresitization and listvenitization occur along the margins of quartz veins and also form independent alteration zones within the intrusion (Kovalev et al., 2009). A prominent NE-trending beresitic zone in the central part of the intrusive body hosts disseminated gold mineralization. Alteration zones surrounding individual quartz veins may reach approximately 20 m in width.

Two principal styles of gold mineralization are recognized at Balazhal: quartz-vein mineralization and veinlet-disseminated to disseminated gold-sulfide mineralization hosted by hydrothermally altered gabbro-dioritic rocks (D'yachkov et al., 2022; Kovalev et al., 2009). Quartz veins occur both within the intrusion and locally in the surrounding hornfelsed sedimentary rocks, whereas the disseminated mineralization is largely confined to the intrusive body. Approximately 40 gold-bearing quartz veins have been described within the deposit, commonly surrounded by halos of stockwork and disseminated mineralization (Kovalev et al., 2009).

The geometry of mineralization changes with structural level. Quartz-vein mineralization predominates in the upper part of the system, whereas stockwork and disseminated mineralization hosted by beresitized intrusive rocks becomes increasingly important at intermediate and deeper levels. Mineralized beresite zones locally reach approximately 140 m in thickness and can be traced for 500–600 m along strike, while mineralization associated with the deeper fault-controlled zone is reported over widths of approximately 5–25 m. At depth, vein-dominated mineralization progressively gives way to veinlet-disseminated and disseminated styles (Kovalev et al., 2009).

These relationships indicate a strong spatial association among the intrusive body, fault and fracture networks, hydrothermal alteration, and the distribution of gold mineralization. This

structural framework provides the basis for evaluating the mineralogical characteristics and vertical organization of the Balazhal hydrothermal system.

4. RESULTS

4.1. Host Rocks and Hydrothermal Alteration

The gold mineralization at the Balazhal deposit is spatially associated with a differentiated mafic to intermediate intrusive body composed predominantly of gabbro-diorite and diorite. Hydrothermal alteration is widespread within the intrusive rocks and is particularly well developed along fracture zones and around quartz veins and veinlets.

The most characteristic alteration type associated with gold mineralization is beresitization. Beresitized rocks are distinguished by the progressive replacement of primary magmatic minerals by quartz, sericite, carbonate minerals, and sulfides. Relict magmatic textures are locally preserved, although strongly altered samples show extensive replacement of the primary mineral assemblage. Pyrite and arsenopyrite are the dominant sulfide minerals within the altered rocks and occur as disseminated grains, aggregates, and veinlet-related mineralization.

The intensity of beresitization varies considerably across the mineralized zones (Figure 2). Weakly altered gabbro-diorites preserve much of their original texture and mineral assemblage, whereas strongly altered rocks are characterized by extensive quartz-sericite-carbonate replacement and increased abundance of sulfide minerals. Pyrite occurs as disseminated grains and locally forms veinlets within the altered rocks.

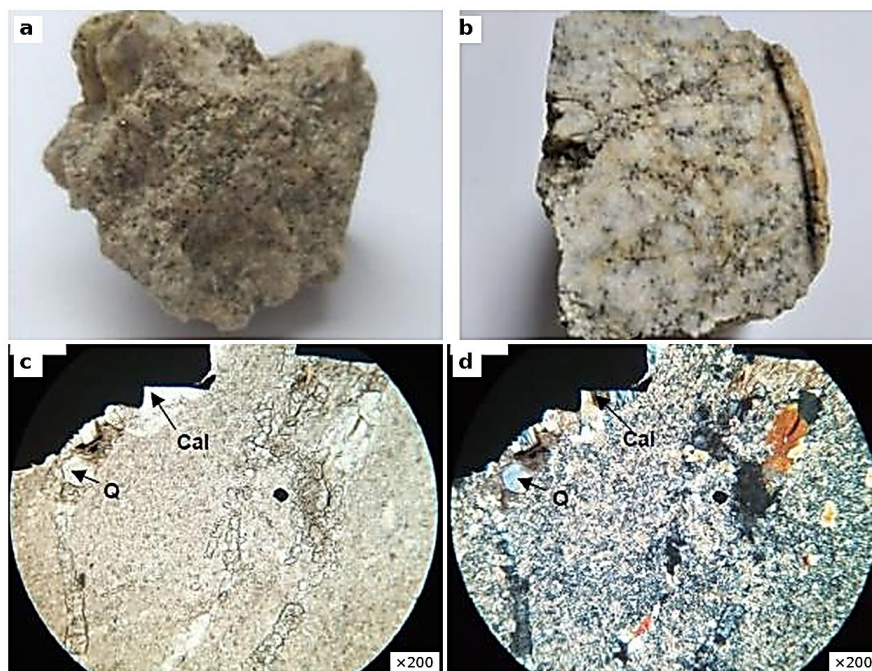


Figure 2. Representative hydrothermally altered rocks of the Balazhal gold deposit. (a, b) Pyrite-bearing beresitized intrusive rocks showing disseminated and veinlet sulfide mineralization; (c, d) quartz-sericite-carbonate alteration of beresitized rocks in plane-polarized (c) and cross-polarized light (d). Qz—quartz; Cal—calcite. Photomicrographs (c, d): ×200.

Note – Prepared by the authors

Beresitic alteration also occurs as halos surrounding individual quartz veins. These alteration halos contain disseminated pyrite and arsenopyrite and locally grade outward into less intensely altered intrusive rocks. In the central part of the intrusive body, more extensive zones of beresitized rocks contain veinlet-disseminated and disseminated sulfide mineralization.

The observed spatial association between beresitization, sulfide mineralization, and fracture-controlled quartz veining indicates that hydrothermal alteration was closely linked to the development of the mineralized system. The mineralogical relationships between alteration minerals, sulfides, and gold are considered in the following sections.

4.2. Ore Mineralogy

Ore mineralization at the Balazhal deposit is dominated by sulfide minerals associated with quartz-vein and veinlet-disseminated mineralization. The principal ore minerals identified in the studied samples are pyrite and arsenopyrite, accompanied by subordinate chalcopyrite and other minor sulfide phases. Native gold occurs both in association with sulfide minerals and as free grains within quartz-bearing assemblages.

4.2.1. Pyrite

Pyrite is the most abundant sulfide mineral in the studied ores and occurs in both quartz-vein and disseminated mineralization. In beresitized gabbro-diorites, it forms disseminated euhedral to subhedral grains and aggregates distributed within the quartz-sericite-carbonate matrix. Individual grains commonly occur in close association with arsenopyrite.

Pyrite also occurs within quartz veins and veinlets, where it forms isolated grains, aggregates, and locally fracture-controlled mineralization. Some grains show irregular margins, internal fractures, and evidence of partial replacement by later sulfide minerals. These textural relationships indicate that pyrite formation accompanied more than one stage of hydrothermal mineralization.

4.2.2. Arsenopyrite

Arsenopyrite is the second major sulfide mineral associated with gold mineralization at Balazhal. It is particularly characteristic of veinlet-disseminated ores hosted by strongly beresitized intrusive rocks. Arsenopyrite commonly forms euhedral to subhedral prismatic grains and aggregates and occurs both independently and in association with pyrite.

In addition to the dominant pyrite-arsenopyrite association, arsenopyrite locally occurs together with minor Bi-bearing and accessory minerals. BSE observations show bastnäsite (Bst) associated with ingodite (Ing) and native bismuth (Bi) in an arsenopyrite-rich matrix (Figure 3a). Bastnäsite also occurs as individual grains along fractures in arsenopyrite (Figure 3b). These minerals are subordinate and do not constitute a major component of the ore assemblage.

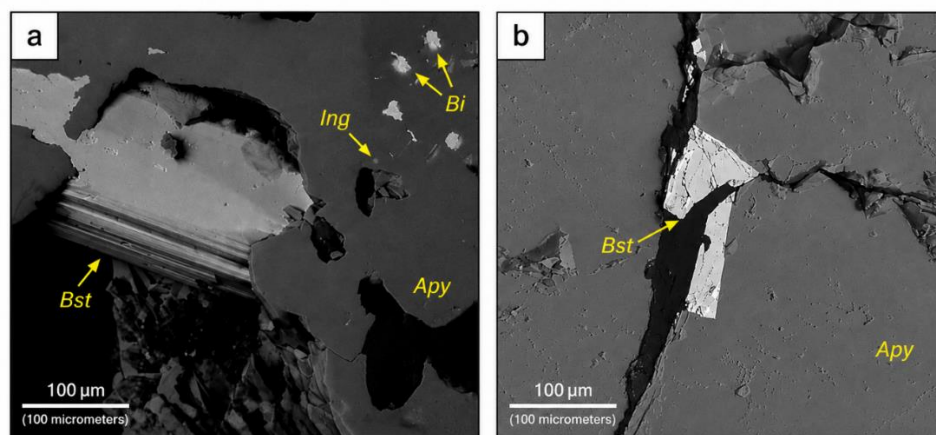


Figure 3. BSE images of bastnäsite and associated Bi-bearing minerals from the Balazhal gold deposit: (a) Bastnäsite (Bst) associated with ingodite (Ing), native bismuth (Bi), and arsenopyrite (Apy); (b) bastnäsite (Bst) occurring along a fracture in arsenopyrite (Apy). Scale bars: 100 μm.

Note – Prepared by the authors

4.2.3 Minor and Accessory Ore Minerals

Chalcopyrite is the most common subordinate sulfide mineral in the studied ores. It occurs as isolated grains, small inclusions, and intergrowths with the dominant sulfide minerals. Other accessory ore phases are considerably less abundant and generally occur as small inclusions or local intergrowths within sulfide-rich assemblages.

BSE observations revealed a number of rare accessory minerals associated with arsenopyrite. These include native bismuth and ingodite, which occur together with bastnäsite in the arsenopyrite-rich assemblage (Figure 3). Bastnäsite is also observed as individual grains along fractures in arsenopyrite. These phases are locally developed and represent only a minor component of the studied mineralization.

A more diverse assemblage of subordinate sulfides and sulfosalts occurs in the quartz-bearing mineralization. Chalcopyrite, sphalerite, tennantite $\pm$ tetrahedrite, galena, and marcasite are present in different proportions, particularly in the later quartz–polymetallic and quartz–carbonate assemblages. Their paragenetic relationships are considered in Section 4.4.

Overall, the ore mineralogy of the studied samples is dominated by pyrite and arsenopyrite, whereas the accessory minerals have a more restricted distribution and are mainly associated with particular mineral assemblages and stages of mineralization.

4.2.4. Mineral Assemblages

Two principal ore associations are distinguished in the studied samples. The first is a pyrite–arsenopyrite association developed mainly in beresitized gabbro–diorites. Pyrite and arsenopyrite occur as disseminated grains, aggregates, and veinlet-related mineralization and are accompanied by fine-grained native gold and minor accessory minerals.

The second is a quartz–sulfide association developed mainly in quartz veins and veinlets. It contains pyrite and arsenopyrite together with subordinate chalcopyrite, sphalerite, sulfosalts, and native gold. In this association, native gold occurs mainly within quartz-rich domains, along quartz–sulfide boundaries, and locally in association with sulfide–sulfosalt aggregates.

The two associations differ primarily in ore texture, host-rock alteration, and the mode of gold occurrence. The pyrite–arsenopyrite association is characteristic of the veinlet–disseminated mineralization in beresitized intrusive rocks, whereas the quartz–sulfide association is typical of the vein-dominated mineralization.

4.3. Native Gold Occurrence and Morphology

Native gold at the Balazhal deposit occurs in several textural settings. The main modes of occurrence are fine-grained gold associated with pyrite and arsenopyrite, free native gold in quartz veins, and less abundant gold associated with late quartz–carbonate–sulfide assemblages.

In the veinlet–disseminated ores hosted by beresitized intrusive rocks, native gold is closely associated with pyrite and arsenopyrite. Fine gold particles occur within sulfide aggregates, along grain boundaries, and in microfractures. Gold is also observed in interstitial positions between quartz and sulfide grains and locally forms irregular overgrowths on sulfide minerals. These occurrences are characteristic of the pyrite–arsenopyrite mineralization developed in strongly altered rocks.

Fine native gold is also observed in close intergrowth with arsenopyrite within quartz veins (Figure 4). The gold forms small irregular particles located along the margins and internal discontinuities of arsenopyrite grains.

In quartz-vein ores, native gold occurs predominantly within quartz-rich domains. It forms irregular grains in interstitial spaces between quartz grains, occurs along microfractures, and locally occupies cavities related to sulfide alteration. Fine accumulations of native gold are also observed in quartz, whereas some pyrite grains show local gold overgrowths.

A less abundant type of native gold occurs in quartz–carbonate veinlets. Here, gold is associated with a more diverse mineral assemblage that includes galena and tennantite. Locally,

droplet-shaped native gold particles reaching approximately 0.2×0.3 mm occur along quartz grain boundaries. Calaverite is also reported from this assemblage.

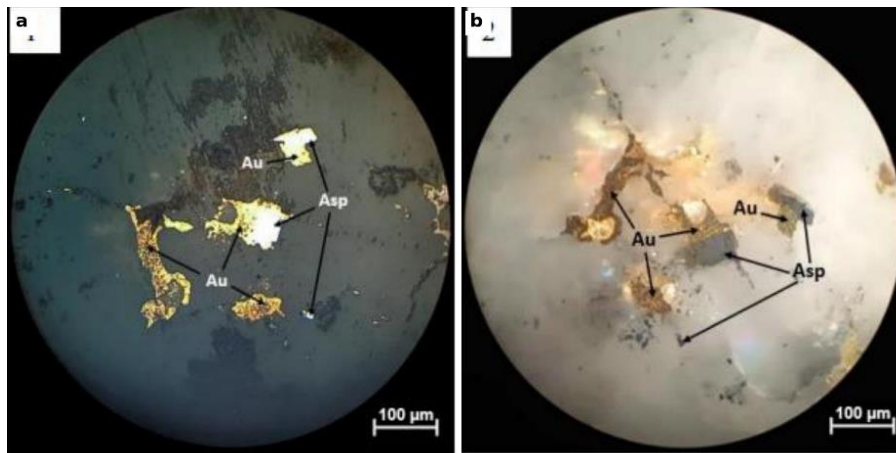


Figure 4. Native gold associated with arsenopyrite in the Balazhal gold deposit. (a, b) Fine native gold (Au II) intergrown with arsenopyrite II (Asp) in a quartz vein, shown in plane-polarized (a) and cross-polarized light (b). Scale bars: 100 μ m.

Note – Prepared by the authors

Thus, two main modes of native gold occurrence are evident in the studied ores: fine-grained gold closely associated with the pyrite–arsenopyrite mineralization and comparatively coarser free gold hosted mainly by quartz and quartz–carbonate assemblages. The textural differences between these occurrences are further considered in the reconstruction of the mineralization sequence.

4.4. Mineralization Stages and Paragenetic Sequence

Textural relationships among alteration minerals, sulfides, gangue minerals, and native gold indicate a multistage evolution of the Balazhal hydrothermal system. Four principal stages can be distinguished: (I) early hydrothermal–metasomatic alteration, (II) formation of disseminated gold–sulfide mineralization, (III) early hydrothermal quartz–polymetallic mineralization, and (IV) late quartz–carbonate mineralization.

Stage I. Early hydrothermal–metasomatic alteration

The earliest stage is characterized by extensive alteration of diorite and quartz diorite and the formation of beresite assemblages dominated by sericite, quartz, carbonate, and albite. Pyrite and arsenopyrite occur as disseminated grains and metacrysts within the altered rocks. In the more mafic peripheral parts of the intrusion, this alteration is represented predominantly by listvenitic assemblages containing dolomite, ankerite, calcite, quartz, and chlorite.

Stage II. Disseminated gold–sulfide mineralization

The second stage represents the principal development of veinlet–disseminated mineralization within the beresitized intrusive rocks. The characteristic ore assemblage is dominated by pyrite + arsenopyrite + quartz + gold, with locally reported gersdorffite. Fine-grained gold is closely associated with pyrite and arsenopyrite and occurs within sulfide grains, along internal discontinuities, and in microfractures. This stage is spatially concentrated in the central part of the intrusive body, where diorite and quartz diorite underwent the most intense beresitic alteration. The close textural relationship between gold and the pyrite–arsenopyrite assemblage distinguishes this mineralization from the later quartz-vein assemblages.

Stage III. Quartz–polymetallic mineralization

The third stage is characterized by quartz-vein and veinlet mineralization containing a more compositionally diverse ore assemblage. Pyrite is accompanied by chalcopyrite, sphalerite,

sulfosalts, and native gold. Tennantite is the dominant sulfosalt reported in this assemblage, whereas tetrahedrite is less abundant. Native gold occurs both within quartz and in association with sulfide–sulfosalt aggregates. The characteristic assemblage can therefore be summarized as: quartz + pyrite + chalcopyrite + sphalerite + tennantite ± tetrahedrite + native gold. The original mineralogical observations record later pyrite aggregates closely associated with chalcopyrite, sphalerite, sulfosalts, and native gold.

Stage IV. Late quartz–carbonate mineralization

The latest primary hydrothermal stage is represented by quartz–carbonate veinlets containing a relatively diverse but subordinate ore assemblage. Calcite, quartz, pyrite, marcasite, galena, arsenopyrite and cobalt-bearing minerals are reported, together with native gold and locally calaverite. Native gold may form relatively coarse, droplet-shaped particles at quartz grain boundaries and occurs locally in association with galena and sulfosalts.

These relationships define a general paragenetic progression from early alteration and pyrite–arsenopyrite formation through the development of sulfide-associated gold mineralization to later quartz–polymetallic and quartz–carbonate assemblages containing progressively more abundant visible native gold.

Mineral / process	Stage I Alteration	Stage II Au–sulfide	Stage III Quartz–polymetallic	Stage IV Quartz–carbonate
Sericite	—————	—————	———	
Albite	—————	———		
Carbonate	—————	—————	—————	
Quartz	—————	—————	—————	—————
Pyrite	—————	—————	—————	———
Arsenopyrite	—————	—————	———	
Native Au	•	—————	—————	—————
Chalcopyrite			—————	
Sphalerite			—————	
Tennantite ± tetrahedrite			—————	
Galena			———	—————
Marcasite				—————
Calaverite				—————

Figure 5. Paragenetic sequence of hydrothermal alteration and ore mineralization at the Balazhal gold deposit.

Note – Prepared by the authors based on (Kalinin K.R., 2011)

4.5 Spatial Distribution and Vertical Zoning of Gold Mineralization

The distribution of gold mineralization at the Balazhal deposit shows systematic changes in ore morphology, host-rock alteration, and mineral assemblages with structural level. Four morphologically distinct styles are recognized in the source material: upper-level gold–quartz–polysulfide veins, intermediate-level disseminated gold–sulfide mineralization in beresites, deeper mineralized zones, and a superimposed quartz–carbonate–telluride veinlet assemblage.

Quartz-vein mineralization is most prominent in the upper part of the system. Numerous gold-bearing quartz veins occur within the intrusive body and are surrounded by halos of hydrothermally altered and sulfide-bearing rocks. These veins represent the most clearly expressed high-grade mineralization style and contain visible native gold predominantly associated with quartz.

At intermediate structural levels, veinlet–disseminated and disseminated gold–sulfide mineralization becomes increasingly important. This mineralization is hosted mainly by beresitized diorite and quartz diorite and is dominated by pyrite and arsenopyrite. The gold-bearing beresite zone forms a NE-trending body in the central part of the intrusion. Its thickness increases from approximately 60 m in the upper part to as much as 140 m at depth, and the zone dips northwestward at approximately 70°.

The change from vein-dominated to disseminated mineralization is accompanied by a corresponding change in the mode of gold occurrence. Whereas visible free gold is characteristic of the quartz-vein ores, the beresite-hosted ores contain a substantial fine-grained gold component closely associated with pyrite and arsenopyrite. The principal disseminated mineralization is concentrated in the central parts of the intrusive body, particularly within altered diorite and quartz diorite. The source data identify these lithologies as the most favorable hosts for this style of mineralization.

At deeper structural levels, the relative importance of individual quartz veins decreases, whereas broader zones of sulfide-bearing altered rocks become more prominent. Late quartz–carbonate veinlets locally overprint the earlier mineralization and contain native gold together with galena, sulfosalts, and, according to the source mineralogical data, locally occurring gold telluride. This assemblage differs from the dominant pyrite–arsenopyrite mineralization of the beresite-hosted ores.

Taken together, the observed relationships define a vertically organized mineralized system in which the morphology of the ore bodies and the mode of gold occurrence vary with structural position. The upper levels are characterized predominantly by quartz-vein mineralization containing visible native gold, whereas the intermediate and deeper parts are increasingly dominated by beresite-hosted veinlet–disseminated and disseminated pyrite–arsenopyrite mineralization.

5. DISCUSSION

5.1. Structural and Lithological Controls on Gold Mineralization

The distribution of gold mineralization at Balazhal indicates that ore localization was controlled by the combined influence of fault and fracture systems, intrusive-rock lithology, and hydrothermal alteration. Gold mineralization is concentrated within and around the gabbro-diorite–diorite intrusive body, but its distribution is strongly heterogeneous. The most intense veinlet–disseminated mineralization occurs within beresitized diorite and quartz diorite, whereas the more mafic peripheral rocks contain comparatively weak sulfide mineralization. This relationship suggests that lithological control operated primarily through differences in the susceptibility of the intrusive rocks to hydrothermal alteration rather than simply through their primary composition (D'yachkov et al., 2021, 2022; Mizernaya et al., 2019).

Structural permeability appears to have been a fundamental control on both quartz-vein and disseminated mineralization. The intrusive body occurs adjacent to the major Balazhal fault system, whereas subsidiary NE-trending fractures control numerous quartz veins and elongated zones of beresitic alteration. The coexistence of vein and disseminated mineralization therefore reflects different expressions of fluid flow within the same structurally controlled hydrothermal system: focused fluid flow along open fractures promoted quartz-vein formation, whereas more distributed fluid–rock interaction within fractured intrusive rocks produced broader zones of beresitic alteration and disseminated sulfide mineralization (D'yachkov et al., 2021, 2022; Mizernaya et al., 2019).

This structural association is consistent with the broader metallogenic architecture of the West Kalba gold belt, where major faults and subsidiary fracture systems exert first-order control on hydrothermal fluid migration and gold deposition. Recent regional syntheses similarly

emphasize structurally controlled mineralized zones and quartz-vein systems as the two dominant styles of gold mineralization in Eastern Kazakhstan.

The close relationship between mineralization and dioritic intrusive rocks is particularly significant at Balazhal. The gold-bearing beresite zones are preferentially developed within diorite and quartz diorite, whereas gabbro-diabase appears less favorable for intense disseminated mineralization. This distribution may reflect differences in fracture behavior, permeability, and fluid-rock reaction among the intrusive lithologies. However, the available data do not allow the relative importance of these factors to be quantified, and therefore the intrusive rocks are interpreted here primarily as favorable structural and lithological hosts rather than necessarily as the source of the ore-forming fluids or metals.

5.2. Beresitization, Sulfidation, and Gold Deposition

The mineralogical relationships observed at Balazhal indicate a close connection between beresitic alteration, sulfidation, and gold deposition. Beresitization transformed the primary dioritic rocks into quartz-sericite-carbonate-albite assemblages and was accompanied by the formation of pyrite and arsenopyrite. The strongest disseminated gold mineralization occurs where this alteration is most intense.

Pyrite and arsenopyrite represent the principal sulfide minerals associated with fine-grained gold. Native gold occurs within and along the margins of sulfide grains, fills microfractures, and locally forms irregular overgrowths on pyrite and arsenopyrite. These textures indicate that the sulfides played an important role in concentrating gold during the development of the disseminated mineralization. Studies of Au-bearing arsenopyrite from orogenic systems document an evolution from early pyrite-arsenopyrite-sericite-quartz assemblages toward polymetallic and later carbonate-bearing mineralization (Filimonova et al., 2020; Kovalev et al., 2011; Stepanov et al., 2021).

Comparable relationships are characteristic of other gold systems of the West Kalba belt. At the Zhaima deposit, for example, the principal primary ores comprise Au-bearing arsenopyrite and pyrite with submicroscopic native gold inclusions (Kalinin et al., 2016). At Suzdal, both visible and invisible gold occur within a multistage hydrothermal system containing pyrite, arsenopyrite and later sulfide assemblages (Kovalev et al., 2009, 2011). More broadly, recent studies of Au-bearing arsenopyrite from orogenic systems document an evolution from early pyrite-arsenopyrite-sericite-quartz assemblages toward polymetallic and later carbonate-bearing mineralization (Stepanov et al., 2021; Sugiono et al., 2025).

The Balazhal assemblage therefore fits a regional pattern in which sulfidation of hydrothermally altered rocks represents an important mechanism of gold concentration (Kalinin et al., 2016; Kovalev et al., 2009, 2011). Nevertheless, the present SEM-EDS dataset primarily establishes mineral associations and textural relationships. Without *in situ* trace-element analyses of pyrite and arsenopyrite, the proportion of structurally bound or nanoscale gold within these sulfides cannot be quantified. Consequently, the term sulfide-associated gold is preferable here to stronger statements concerning “invisible gold” unless supported by additional LA-ICP-MS or comparable analytical data (Filimonova et al., 2020).

5.3. Evolution of Gold Occurrence During Ore Formation

An important feature of Balazhal is the systematic change in the mode of gold occurrence between mineralization stages. The early disseminated ores are characterized predominantly by fine-grained gold associated with pyrite and arsenopyrite, whereas later quartz-bearing assemblages contain more readily visible native gold.

This change is accompanied by increasing mineralogical diversity. The pyrite-arsenopyrite assemblage characteristic of beresitized rocks is followed by quartz-polymetallic mineralization containing chalcopyrite, sphalerite, tennantite and subordinate galena. Native gold occurs in quartz, at quartz-sulfide boundaries, and within composite sulfide-sulfosalt aggregates. Late

quartz–carbonate veinlets contain an additional assemblage involving galena, marcasite and locally reported calaverite.

Thus, the observed mineralogy is better explained by multistage redistribution and deposition of gold than by a single gold-forming event. Similar multistage redistribution of sulfides and gold has been documented at the Suzdal deposit in the West Kalba belt (Kovalev et al., 2009, 2011).

At Balazhal, the progression can be summarized as: *beresitization* → *pyrite–arsenopyrite sulfidation and fine-grained Au* → *quartz–polymetallic mineralization with free Au* → *late quartz–carbonate ± telluride mineralization*.

This sequence provides an important link between alteration mineralogy and the changing physical occurrence of gold. Rather than representing two completely independent ore types, the disseminated and quartz-vein ores appear to record different stages and structural expressions of a complex hydrothermal system.

A comparable multistage evolution of gold occurrence has recently been documented at the Southern Ashaly deposit in East Kazakhstan, where successive pyrite, pyrite–arsenopyrite, sulfide, and polymetallic mineralization stages were distinguished. Two generations of native gold were identified, with early gold associated with the pyrite–arsenopyrite assemblage and later high-fineness gold related to subsequent sulfide mineralization (Greku et al., 2024, 2025). The Balazhal mineralization shows a broadly comparable transition from fine-grained sulfide-associated gold in pyrite–arsenopyrite-bearing beresites to more readily visible native gold in later quartz-bearing assemblages. However, this similarity should be regarded as a regional mineralogical analogy rather than evidence for identical ore-forming conditions.

5.4. Vertical Zoning and Genetic Model

The spatial distribution of alteration and ore assemblages at Balazhal indicates a vertically organized hydrothermal system rather than a simple set of isolated quartz veins. The most evident change with structural level is the transition from vein-dominated mineralization in the upper part of the deposit to broader zones of veinlet–disseminated and disseminated mineralization within beresitized intrusive rocks at depth (Figure 6). The source data distinguish upper gold–quartz–polysulfide veins, an intermediate gold–sulfide–beresite assemblage, deeper sulfide-bearing mineralized zones, and a superimposed late gold–quartz–carbonate–telluride assemblage.

The upper structural level is characterized by quartz veins containing native gold and sulfides, including visible/free gold. The intermediate level comprises beresitized diorite–quartz diorite with veinlet–disseminated Py–Apy mineralization and fine-grained native gold. The deeper/root zone is dominated by broad sulfide-bearing alteration with abundant pyrite and arsenopyrite. Late quartz–carbonate veinlets containing polymetallic sulfides and Au–telluride mineralization crosscut the earlier alteration and ore assemblages. Py—pyrite; Apy—arsenopyrite; Au—native gold; Ccp—chalcopyrite; Sp—sphalerite; Tn—tennantite ± tetrahedrite; Gn—galena; Mar—marcasite; Cal—calaverite.

At the upper structural levels, hydrothermal fluid flow was strongly focused along fractures, resulting in the formation of discrete quartz veins containing visible native gold and sulfide minerals. At intermediate levels, mineralization becomes more broadly distributed through the intrusive rocks. Here, intense beresitization is accompanied by disseminated pyrite and arsenopyrite and by fine-grained sulfide-associated gold. The increasing thickness of the gold-bearing beresite zone with depth, from approximately 60 m to as much as 140 m, supports the interpretation that disseminated mineralization represents a volumetrically important component of the system rather than merely narrow alteration halos around individual quartz veins.

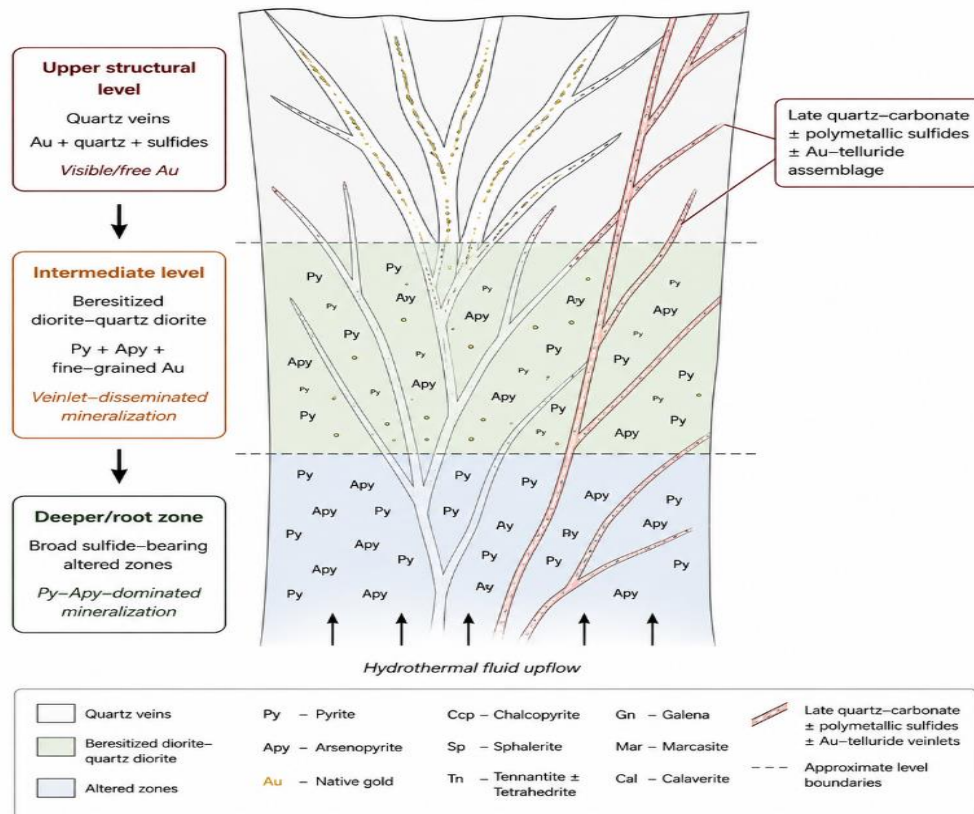


Figure 6. Conceptual model of the vertical zoning of gold mineralization at the Balazhal deposit
Note – Prepared by the authors

This vertical transition is also reflected in the mode of gold occurrence. The quartz-vein ores contain comparatively abundant visible free gold, whereas the veinlet-disseminated ores are characterized by a much closer association of gold with pyrite and arsenopyrite. The source data further indicate that the principal disseminated ore bodies occur at depths of approximately 60–100 m and are preferentially hosted by altered diorite and quartz diorite. This relationship suggests that changes in structural permeability and the intensity of fluid-rock interaction influenced both ore morphology and gold occurrence.

The late quartz-carbonate assemblage requires separate consideration. Although it occurs locally at deeper levels, the observed paragenetic relationships indicate that it represents a superimposed mineralization stage rather than a simple downward continuation of the vertical zonation. It should therefore not be interpreted as the deepest member of a single continuous vertical sequence. Instead, late quartz-carbonate veinlets containing polymetallic sulfides, native gold and locally reported calaverite overprint the earlier beresite-hosted and quartz-vein mineralization. The original mineralogical scheme similarly identifies this assemblage as a late hydrothermal stage (Herzog et al., 2024).

On this basis, the Balazhal system can be interpreted as the product of several interconnected processes. Initial structurally controlled fluid flow produced widespread hydrothermal alteration of favorable intrusive rocks. Beresitization was followed or accompanied by extensive sulfidation and the development of pyrite-arsenopyrite assemblages capable of concentrating fine-grained gold. Continued hydrothermal activity produced fracture-controlled quartz veins and a more compositionally diverse polymetallic assemblage containing visible native gold. Late reopening of fractures resulted in localized quartz-carbonate mineralization (Herzog et al., 2024; Kovalev et al., 2011).

The resulting model therefore links three principal controls on gold distribution at Balazhal: structural permeability, lithologically controlled hydrothermal alteration, and multistage sulfide–gold deposition. The coexistence of quartz-vein and beresite-hosted disseminated ores can consequently be interpreted as spatially and temporally related expressions of the same hydrothermal system. However, in the absence of fluid-inclusion, stable-isotope, and direct geochronological data from the investigated samples, the source and physicochemical evolution of the ore-forming fluids cannot be constrained by the present study.

5.5. Exploration Implications

The recognition of extensive gold-bearing beresite mineralization has direct implications for exploration at Balazhal. Exploration models focused exclusively on high-grade quartz veins may underestimate the potential of broader, lower-grade but volumetrically significant zones of veinlet–disseminated mineralization. The source data show that gold-bearing beresites form bodies tens to more than one hundred metres thick and that their extent increases at depth.

The most prospective targets are therefore not restricted to individual quartz veins. Particular attention should be given to NE-trending fracture zones within diorite and quartz diorite, intense beresitic alteration, and zones of abundant pyrite–arsenopyrite mineralization. The close spatial relationship among these features provides a practical combination of structural, alteration, and mineralogical criteria for targeting concealed mineralization (D'yachkov et al., 2021, 2022; Mizernaya et al., 2019).

The occurrence of fine-grained gold associated with pyrite and arsenopyrite also has implications for ore characterization. Quartz-vein and disseminated beresite-hosted ores should not automatically be treated as mineralogically equivalent because their dominant modes of gold occurrence differ. This distinction should be considered during future mineral-processing and metallurgical investigations (Filimonova et al., 2020; Kovalev et al., 2011; Stepanov et al., 2021).

6. CONCLUSIONS

The study of the Balazhal gold deposit allows the following conclusions to be drawn:

- two main styles of gold mineralization are recognized: quartz-vein mineralization and veinlet–disseminated gold–sulfide mineralization hosted mainly by beresitized diorite and quartz diorite. Pyrite and arsenopyrite are the dominant sulfide minerals of the disseminated ores;
- the mode of gold occurrence changes between the mineralization stages. Fine-grained native gold is closely associated with pyrite and arsenopyrite in beresitized rocks, whereas comparatively coarser free gold occurs mainly in quartz veins. Late quartz–carbonate assemblages contain native gold together with polymetallic sulfides, sulfosalts, and locally reported gold tellurides;
- the mineralogical relationships indicate a multistage hydrothermal evolution comprising early hydrothermal alteration, pyrite–arsenopyrite gold–sulfide mineralization, quartz–polymetallic mineralization, and late quartz–carbonate mineralization;
- gold mineralization shows a distinct vertical organization. Quartz-vein mineralization is more characteristic of the upper structural levels, whereas broader zones of beresite-hosted veinlet–disseminated pyrite–arsenopyrite mineralization become increasingly important at depth. Therefore, the deeper parts of the altered diorite–quartz diorite body, particularly along NE-trending fracture zones, remain important targets for further exploration.

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