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HYDROTHERMAL ALTERATION TYPES IN THE ZAFAR INTERMEDIATE EPITHERMAL CU-AU DEPOSIT: IMPLICATIONS FOR TECTONIC SETTING AND MAGMATIC EVOLUTION

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Abstract

The Zafar copper-gold deposit is located Gadabay ore district, 3.5 km northwest of the Gadabay gold mine and 2.5 km southwest of the Ugur mine. This newly discovered copper-gold deposit contains 6.8 million tonnes of measured resources (0.5% Cu, 0.4 ppm Au, and 0.6 % Zn, according to Zafar JORC Mineral Resource Estimate Update Report 2022). This study investigates the spatial and mineralogical characteristics of hydrothermal alteration zones within the Zafar deposit and evaluates the influence of tectonic regime and magmatic activity on their development and distribution. Detailed field observations, petrographic analyses, and geochemical data reveal a well-defined alteration zonation consisting of argillic (minerals: pyrophyllite, kaolinite, alunite, diaspore, dickite, quartz), phyllic (minerals: sericite, illite, quartz, pyrite), propylitic (minerals: chlorite, epidote, albite, calcite, actinolite, pyrite) and silification assemblages, typical of intermediate sulfidation epithermal systems.

Keywords: *Zafar, hydrotermal alteration, kaolinite, tectonic setting*

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Geological setting of the area

Zafar intermediate epithermal Cu-Au deposit a new discovered in its Gadabay ore district in the Lesser Caucasus region of Azerbaijan. Zafar was discovered following a ZTEM geophysical survey and follow-up field mapping and ground geophysical surveying of three ZTEM targets. This area was considered a high priority target as part of the initial ZTEM report ranking. The target area has been designated “Zafar” and its centre is located approximately 3.8 km NW of the Gedabek open pit and 2.5 km SW of the Ugur mine (Fig.1). Mineralisation in the area was discovered by AIMC geologists based on complex data interpretation [6]. The Gadabay ore district is one of the main producing mining districts of Azerbaijan and is the largest porphyry-epithermal ore field of the country. Ore district belongs to the Lok-Karabakh structure zone. Within the Azerbaijani sector of the Lesser Caucasus Megaanticlinorium, four structural-formational zones (or metallogenic zones) are recognized: the Lok-Karabakh, Goycha-Hakari, Miskhana-Zangezur and Araz zones. The Lok-Karabakh structural-formational zone, which hosts the Gadabay ore district, is associated with island arc volcanism. The ore district, located within the bounds of the Shamkir uplift and characterized by a complex geological structure, is composed of Middle and Upper Jurassic sedimentary units that are intruded by igneous bodies of varying ages and compositions and disrupted by fault structures. The Lok-Karabakh structural-formational zone represents one of the key metallogenic and tectonic domains of the Lesser Caucasus. It is associated with Jurassic–Cretaceous island arc magmatism formed as a result of subduction processes along the northern margin of the Tethys Ocean [3].

The ore deposits and prospects of the district are spatially related to the emplacement of quartz-diorite and granodioritic porphyritic stocks and dikes postdating the Gadabay intrusion and the Middle Jurassic Atabay-Slavyanka plagiogranite [2].

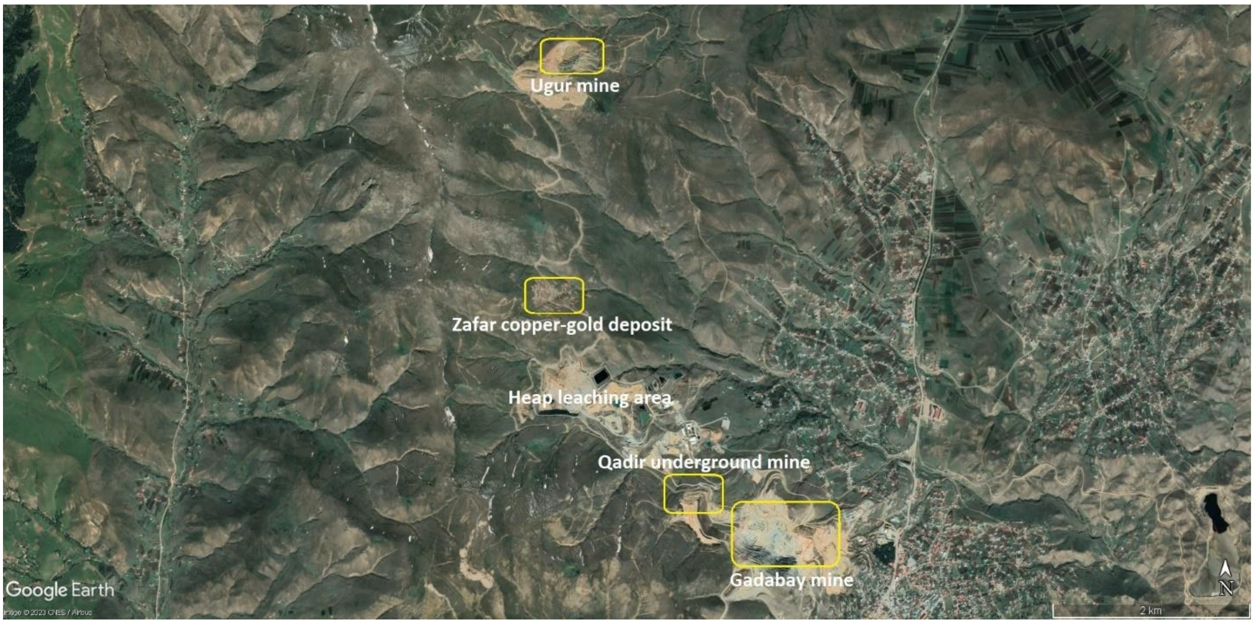


Fig. 1. Location scheme of Zafar copper-gold deposit according to Gadabay and Ugur mines (by Google Earth program).

The Zafar mineralization zone is situated within the Gadabay ore district of the Shamkir anticlinorium and covers the northeastern and eastern slopes of Mount Gyzyljadagh within the boundaries of the Gadabay-Bittibulag deep-seated fault zone. According to Babazadeh et al. [2]. the ore deposits of the Gadabay district are controlled by a deep-seated, ~NS oriented, orogen-transverse arc-shaped fault.

The Zafar intermediate Cu-Au epithermal deposit is situated on the southeastern side of the Mollali-Garadagh syncline and the northeastern section of the Arıqdam-Shakarbey anticline. Within this deposit, the Upper Bajocian stage is characterized by the presence of rhyolite-dacite lava and pyroclastic facies, which are intersected by various fault systems. These facies are extensively spread across the geological framework of the mineralization zone and extend along the eastern flank of Mount Gyzyljadagh.

In the Zafar deposit, the Lower Bajocian rocks are mainly represented by andesite porphyries. In certain areas, explosive breccias of different sizes (ranging from 1–3 cm to 5–8 cm) can be found interspersed between layers of andesitic tuff. The thickness of the andesitic units within the deposit does not exceed 250 meters in horizontal erosional sections. The Lower Bajocian period witnessed significant effusive magmatism, which is linked to the development of deep crustal fault systems during that era. These volcanic activities resulted in a complex of intermediate-composition volcanogenic and volcanogenic-sedimentary rocks, including andesitic lava breccias and tuffs, which appear as both flows and cover formations. In the central area of the deposit, clastic sediments of varying thickness from the Quaternary and Holocene acumulation. These sediments are primarily made up of alluvial and eluvial-deluvial deposits.

Hydrothermal Alteration Types ***and XRD Analysis***

Hydrothermal alteration studies were conducted on samples collected from natural rock outcrops, upper horizons of drilled boreholes, and core samples within the Zafar deposit and its surrounding areas. The investigations were carried out using X-ray Powder Diffraction (XRD) to identify alteration-related minerals. Based on these analyses, alteration distribution maps were generated to illustrate the spatial extent of hydrothermal transformations across the study area (Fig. 3).

Powdered rock samples prepared for XRD analysis of hydrothermal alteration minerals were analyzed using BTX II X-ray Diffraction (XRD) Analyzer and the TERRA II Portable XRD Analyzer. Measurements were conducted at the Exploration Geology Department laboratory of AIMCL, where the samples were dried and ground to <140 microns, with approximately 15 mg of each sample used for analysis. The Olympus BTX XRD device, equipped with a cobalt (Co) X-ray tube, operated under conditions of 30 mA current and 33 kV voltage. Mineralogical identification and semi-quantitative composition, including the relative percentage of minerals and their associated diffractograms, were determined using SwiftMin® and XPowder software packages.

Field observations and analytical data indicate the presence of distinct types of hydrothermal alteration in the area, including argillic, phyllic, propylitic and silicification. The alteration mineral assemblage is dominated by illite, sericite, montmorillonite, epidote, dickite, kaolinite, albite, and others, which occur across a broad spatial extent (Table 1).

Table 1: Summary of Hydrothermal Alteration Types and Key Indicator Minerals

Alteration Zone	Diagnostic Minerals	Key Features
Argillic	pyrophyllite, kaolinite, alunite, diaspore, dickite, quartz	typically near surface or fluid upflow zones, clay-dominated, moderate alteration intensity, high-acidity conditions
Phyllic	sericite, illite, quartz, pyrite	strong alteration, associated with quartz-sericite-pyrite veins
Propylitic	chlorite, epidote, albite, calcite, actinolite, pyrite	distal alteration, common in mafic/intermediate host rocks
Silicification	quartz (microcrystalline, massive, vein), minor accessory minerals	silica enrichment, typically pervasive or vein-hosted

Argillic alteration is predominantly developed in the central part of the deposit and exhibits a broader spatial distribution compared to other alteration types. This alteration is primarily characterized by the extensive development of clay minerals such as pyrophyllite, kaolinite, dickite, and quartz, with minor occurrences of alunite within the altered zones.

Argillic alteration typically forms through intense hydrogen ion (H^+) metasomatism (acid leaching) under low-temperature hydrothermal conditions, generally ranging from 100°C to 300°C. The alteration process primarily affects plagioclase feldspars and mafic silicate minerals such as hornblende and biotite. Kaolinite, which commonly replaces plagioclase, is the most abundant clay mineral in this assemblage, whereas quartz tends to remain unaltered. Alunite, along with jarosite and natrojarosite (identified in some of the studied samples), is also recognized as a diagnostic mineral of this alteration type.

Propylitic alteration is primarily observed within the andesitic tuff formations situated in the outer regions of the deposit. The extent and intensity of this alteration are significantly influenced by the variations in permeability found within the tuffaceous units. Although alteration is widespread, some original volcaniclastic textures are preserved in certain areas.

The characteristic alteration mineral assemblage includes chlorite, epidote, albite, calcite, actinolite, and disseminated pyrite. Petrographic examinations show that chlorite preferentially replaces volcanic clasts, whereas epidote is more commonly disseminated throughout the groundmass, often occurring alongside chlorite. In certain horizons, epidote displays selective replacement features, likely reflecting focused fluid flow along preferential pathways. Additionally, microscopic analysis has revealed a localized replacement of the matrix by magnetite, indicating minor iron enrichment during alteration.

The origin of the propylitic alteration remains a subject of interpretation. It is currently uncertain whether this alteration is the result of contact metamorphism associated with the emplacement of dioritic intrusions into the tuffaceous host rocks, or if it reflects a distal expression of a broader hydrothermal alteration system related to epithermal mineralization processes.

Propylitic alteration is induced by hydrothermal fluids rich in iron and magnesium, which alter mica or amphibole [4]. One of the reactions associated with this process may have occurred as described below [11]:

$$KAl_3Al_3(OH)_2+3H_4SiO_4+9Fe^{2+}6Mg^{2+}+18H_2O \rightleftharpoons 3Mg_2Fe_3Al_2Si_3O_{10}(OH)_8+2K^{+}+26H^{+}$$

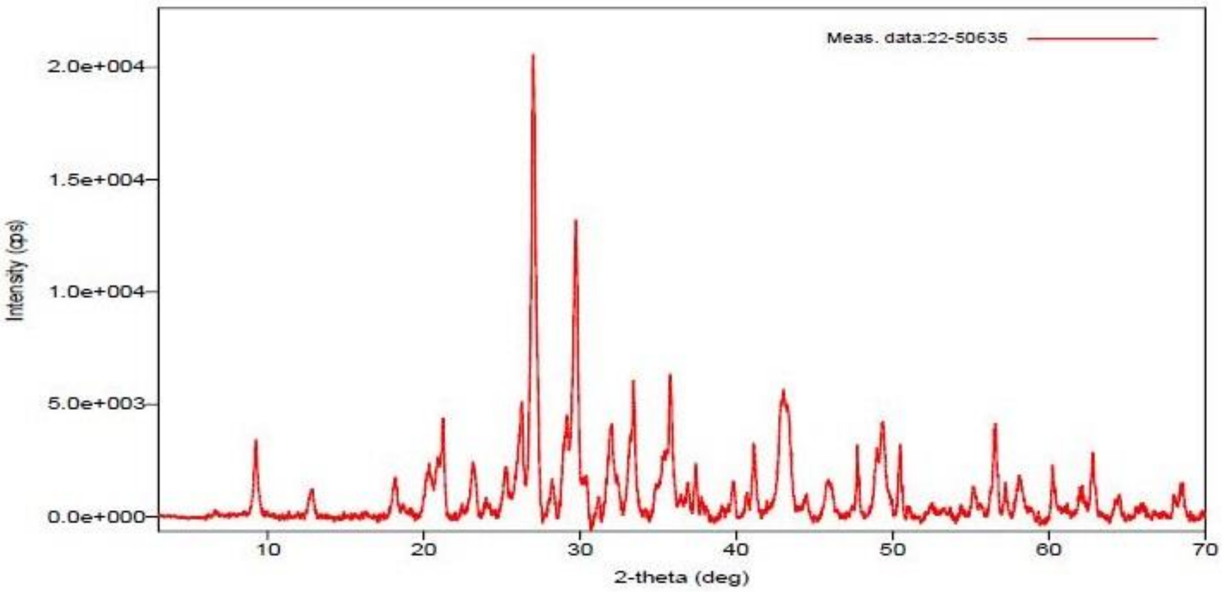
muscovite *fluid* *chlorite* *fluid*

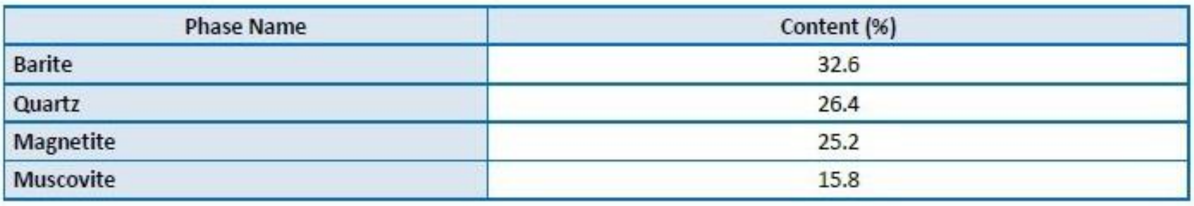
Phyllic alteration is primarily observed in the northeastern sector of the deposit. This alteration zone, often referred to as sericitic alteration, is typically situated adjacent to the argillic zone, and in some instances, the boundary between the two is difficult to delineate due to their overlapping mineralogical characteristics. The phyllic zone is mainly characterized by the presence of illite, quartz, pyrite, and sericite (fine-grained muscovite).

Phyllic alteration represents an acidic hydrothermal process, primarily driven by the breakdown of feldspar minerals in the presence of hydrogen ions (H^+), hydroxyl (OH^-), potassium (K), and sulfur (S). This reaction results in the formation of quartz, white mica (sericite), pyrite, and occasionally chalcopyrite. Depending on the composition of the original rock, by-products such as albite and additional quartz may also form. Sericitization commonly leads to a depletion of calcium (Ca) and sodium (Na), accompanied by either an enrichment or loss of potassium (K). The representative chemical reaction of this alteration process has been proposed by Mathieu [11]:

$$3NAlSi_3O_8 + 2H^{+} \leftrightarrow KAl_3Si_3O_{10}(OH)_2 + 3Na^{+} + 6SiO_2$$

albite *fluid* *muscovite* *fluid* *quartz*





Phase Name	Content (%)
Barite	32.6
Quartz	26.4
Magnetite	25.2
Muscovite	15.8

Fig.2. XRD pattern and mineralogical results of sample from drill hole 21GED16 within the massive pyrite zone exhibiting phyllic (?) alteration.

Silification alteration-microscopic examination of thin sections, complemented by field observations, has identified localized zones of silicification within the exploration area. In these zones, secondary quartz is observed intergrown with primary, coarse-grained quartz crystals-an indication of pervasive silicification. The presence of secondary quartz within the groundmass or along microfractures serves as a diagnostic feature of this alteration type, suggesting the introduction of silica-rich hydrothermal fluids during post-depositional processes.

The primary zone of ore mineralization within the Zafer area is spatially correlated with a montmorillonite–pyrophyllite hydrothermal alteration assemblage. This mineral association is interpreted as a key indicator of mineralization and has been delineated both at the surface outcrops and in drill core observations. Overlying this core zone, a sequence of alteration zones characterized by illite–sericite, dickite–kaolinite, and kaolinite assemblages is present, suggesting progressive zonation outward from the center of mineralization.

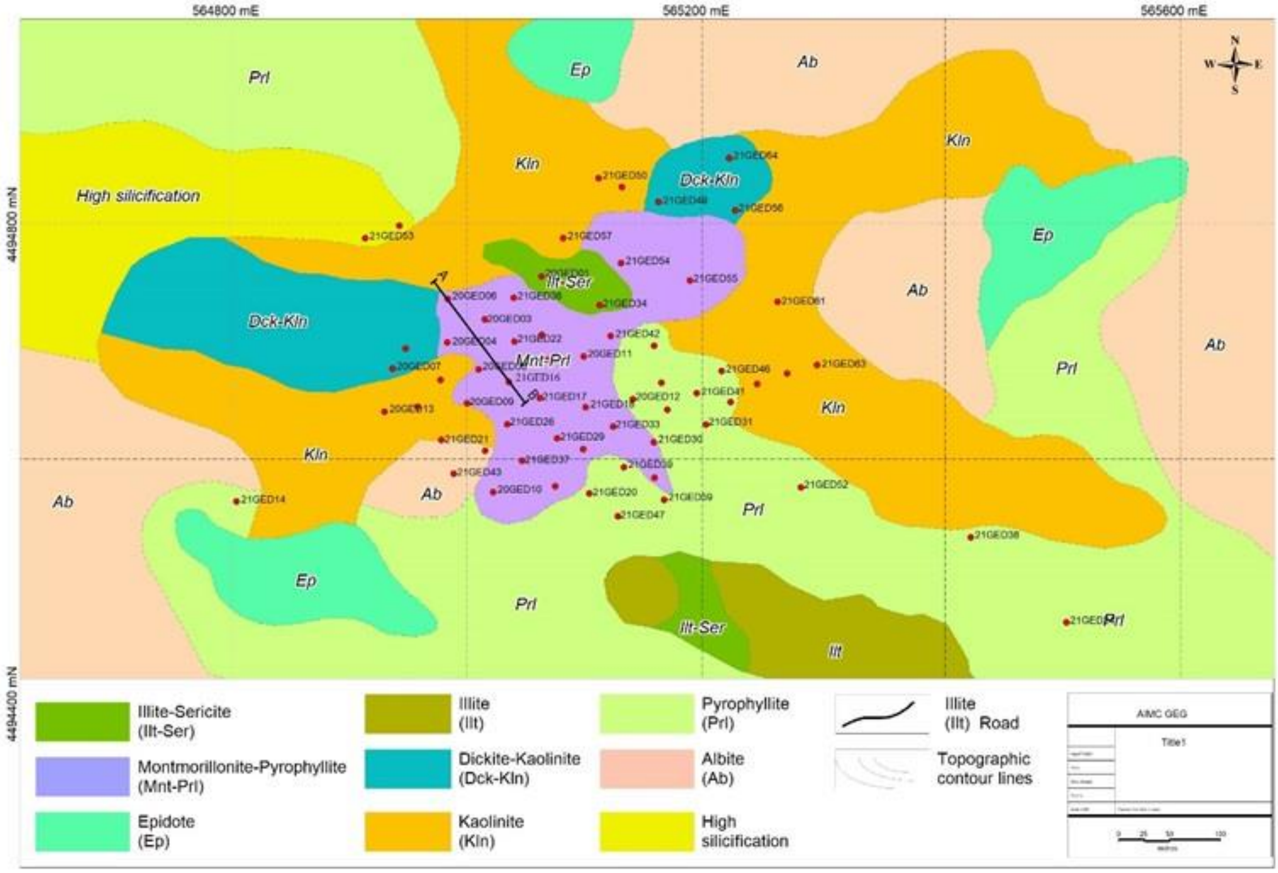


Fig. 3. Alteration map of the Zafar exploration area illustrating the spatial distribution of hydrothermal alteration zones based on XRD analyses and field observations.

Surface alteration mapping and drill core data consistently identify the montmorillonite–pyrophyllite assemblage as the dominant alteration type associated with the mineralized core. Additionally, sericite and kaolinite are frequently observed within this interval, reflecting overprinting alteration effects or transitional alteration zones.

In the vicinity of the ore body, particularly in drill hole 21GED16, a mineral association composed of sericite–illite–halloysite has been identified. This assemblage is typically observed at the upper contact zone of the ore body, suggesting a stratigraphically controlled alteration pattern or downward fluid evolution.

Within the mineralized zone itself, hydrothermal alteration is dominated by kaolinite, montmorillonite, and dickite, consistent with the advanced argillic alteration type (Figure 4). These minerals likely formed in response to acidic, high-sulfidation fluid conditions during peak hydrothermal activity.

Drill hole 20GED06, which is located outside the main ore-bearing structure, contains similar alteration minerals; however, the mineralogical associations differ significantly. In this non-mineralized context, from approximately 300 meters depth, sericite alteration becomes increasingly prominent, suggesting a broader phyllic overprint not directly related to ore-forming processes.

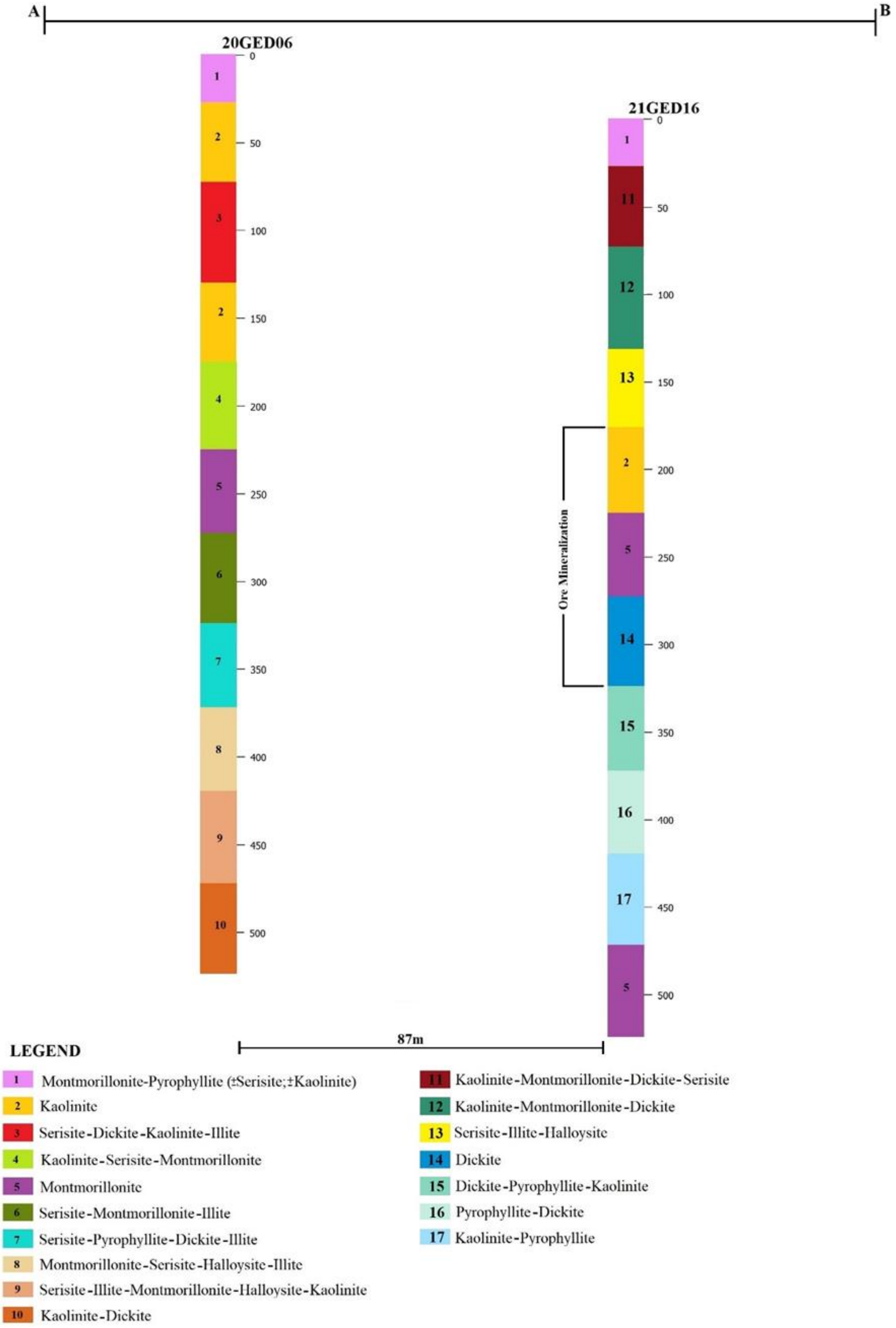


Fig.4. XRD-based hydrothermal alteration cross-section along the A–B line, illustrating the vertical distribution and zonation of alteration minerals.

Implications for Tectonic Setting and Magmatic Evolution

The tectonic regime and associated stress fields play a critical role in determining the type and distribution of hydrothermal deposits within volcanic arc settings. On a regional scale, arc-parallel translithospheric strike-slip fault systems exert a significant influence on magma emplacement in many volcanic arcs. Low-sulfidation deposits are commonly associated with extensional tectonic settings, often developing in arc or post-collisional rift environments. In contrast, intermediate-sulfidation systems typically form under neutral to mildly extensional conditions-similar to high-sulfidation environments-and are linked to subduction-related magmatism characterized by andesitic to dacitic ± rhyolitic compositions [7].

The magmatic fluid is a primary source of many components in the hydrothermal deposits formed in a volcanic arc. These fluids are enriched in metals through several mechanisms, including mantle melting, subduction slab-derived mass transfer, and crustal anatexis. Notably, metals such as gold are found in Fe-Ni sulfide phases within the upper mantle. During partial melting, these sulfides are partially dissolved, releasing their metal contents into ascending basaltic magmas [5].

Isotopic analyses indicate that the magmatic or igneous source of the Gadabay deposit is derived from the upper mantle [1]. These studies further suggest that the Zafar deposit was formed within a volcanic arc environment, driven by subduction-related geodynamic processes. The mineralization is closely associated with the calc-alkaline magmatism of andesitic-dacitic to monzonitic composition [10]. Consequently, the genetic model proposed for the Gadabay deposit may also be applicable to the formation of the Zafar deposit [3].

Conclusion

The Zafar Cu-Au intermediate epithermal deposit, located within the Gadabay ore district of the Lesser Caucasus, represents a significant new discovery within Azerbaijan's primary porphyry-epithermal metallogenic zone. Its geological framework is structurally controlled by deep-seated fault systems and is spatially associated with Jurassic volcanic and subvolcanic rocks, particularly rhyolite-dacite and andesitic facies. The deposit's complex lithological and structural setting highlights its genetic link to subduction-related arc magmatism and positions it as a promising exploration target in the region. The hydrothermal alteration patterns at the Zafar deposit reveal a complex zonation that includes argillic, phyllic, propylitic, and silicification types, each marked by distinct mineral assemblages. These alteration zones reflect variations in temperature, fluid composition, and structural control during the mineralization process. The results contribute to a better understanding of the deposit’s epithermal system and provide important vectors for ongoing exploration and targeting of mineralized zones. The geotectonic and magmatic context of the Zafar and Gadabay deposits highlights the critical role of subduction-related processes and arc-parallel fault systems in controlling hydrothermal mineralization. Isotopic and geochemical evidence supports an upper mantle-derived magmatic source, enriched in metals through partial melting and fluid transfer mechanisms. Given their shared volcanic arc setting and calc-alkaline magmatic affinities, the genetic model of the Gadabay deposit provides a viable framework for understanding the formation of the Zafar deposit.

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