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ARC-RELATED CU-PB MINERALIZATION IN THE HANZAL GRANITE, KOHISTAN BATHOLITH, PAKISTAN: PETROLOGICAL AND GEOCHEMICAL CONSTRAINTS

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Abstract: The Hanzal Cu-Pb polymetallic quartz vein system, emplaced within the Kohistan Batholith of northern Pakistan, constitutes a well-preserved example of arc-related magmatic-hydrothermal mineralization developed in the Kohistan Island Arc during collisional orogenesis. The study area encompasses a composite lithotectonic assemblage of calc-alkaline plutonic rocks (granite to granodiorite), metavolcanic sequences (basalt to basaltic andesite), and metasedimentary units (marble and slate), reflecting a complex magmatic and tectonometamorphic evolution. This study integrates detailed field mapping, petrography, and whole-rock geochemistry to constrain the petrogenetic evolution of the Hanzal granitoids and the metallogenic processes responsible for Cu-Pb mineralization. Ore mineralization is structurally controlled and predominantly confined to quartz veins and veinlet networks, comprising a hypogene sulfide assemblage of chalcopyrite, galena, sphalerite, and pyrite, overprinted by supergene phases including malachite, azurite, hematite, and limonite. Petrographic characteristics indicate that the host intrusions range from monzogranite to granodiorite, dominated by quartz, plagioclase, and K-feldspar, with accessory biotite, muscovite, amphibole, and zircon. Microtextural features, including myrmekitic intergrowths, oscillatory zoning in plagioclase, and brittle deformation of quartz, exhibits progressive magmatic differentiation, syn- to post-emplacement deformation, and pervasive hydrothermal overprinting. Geochemically, the granitoids exhibit calc-alkaline affinity and are interpreted to have originated from partial melting of a metasomatized continental crustal source in a subduction-modified, collision-related tectonic regime. Trace element systematics and compositional variability indicate polyphase magma generation and incremental emplacement, accompanied by fluid exsolution and evolving magmatic-hydrothermal systems. The Cu-Pb mineralization is genetically linked to these magmatic processes, with ore-forming fluids likely derived from late-stage magmatic devolatilization, subsequently modified by fluid-rock interaction and meteoric ingress. The Hanzal system displays key attributes consistent with intrusion-related and porphyry-style mineralization.

Keywords: Kohistan batholith, magmatic-hydrothermal systems, granitoids, porphyry-related systems.

Introduction

Northern Pakistan forms part of the western Himalayas and exhibits prolonged subduction, arc magmatism, and collision between the Indian and Eurasian plates (Tahirkheli, 1979; Kazmi & Jan, 1997). Within this framework, the Kohistan Island Arc represents an accreted intra-oceanic arc bounded by the Main Karakoram Thrust (MKT) and Main Mantle Thrust (MMT) (Sullivan *et al*., 1993; Fig. 1). Its major magmatic component, the Kohistan Batholith, comprises multiphase mafic-felsic intrusions and is noted for porphyry and hydrothermal mineralization (Richards, 2011; Sillitoe, 2010).

The Hanzal Sarot area within the Kohistan Batholith exposes plutonic, metavolcanic, and metasedimentary rocks (granite-granodiorite, basalt-basaltic andesite, marble, slate) recording magmatism, deformation, and fluid-rock interaction favorable for ore formation (Fig. 1). Across the Kohistan Island Arc, diverse mineralization styles, including placer deposits, hydrothermal quartz-sulfide veins, shear-zone-hosted mineralization, and REE enrichment, have been documented (Rahman *et al*., 2015; Hussain *et al*., 2021). Despite its recognized metallogenic potential, the genetic link between granitoid magmatism and polymetallic mineralization at Hanzal remains poorly constrained. Intermediate to felsic intrusions are major sources of Cu-Pb-Zn and precious metal mineralization worldwide (Sillitoe, 2010; Wilkinson, 2013). Emplacement of hydrous, oxidized magmas generates fracture networks, breccias, and vein systems that channel hydrothermal fluids, commonly forming radial and concentric fractures around intrusive centers due to magma-induced stress regimes (Richards, 2015; Tosdal and Richards, 2001; Fig. 1). Hydrothermal fluids released during late-stage magmatic crystallization transport metals and precipitate them in response to cooling, depressurization, and fluid mixing (Heinrich *et al*., 1999; Kouzmanov and Pokrovski, 2012). The resulting

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mineralization is structurally controlled and spatially zoned, forming porphyry and epithermal systems (Simmons *et al*., 2005; Sillitoe, 2010). However, integrated studies linking granitoid petrogenesis, hydrothermal evolution, and Cu-Pb mineralization in the Hanzal Sarot area remain limited.

This study proposes that the Hanzal granitoids originated from an oxidized, subduction-modified crustal source, and that Cu-Pb mineralization is genetically linked to late-stage magmatic fluid exsolution. Fractures, veins, and breccias controlled fluid flow and ore deposition, whereas supergene processes enhanced secondary copper enrichment. Integrated field, petrographic, and whole-rock geochemical data are used to constrain magma evolution, hydrothermal processes, and arc-related Cu-Pb mineralization within the Kohistan Batholith.

Regional Geology

The Himalayas formed by collision between the Eurasian and Indian plates, and northern Pakistan exhibits a complex continental convergence history. Regionally, it is subdivided into three tectonic units: the Karakoram Block, the Kohistan Island Arc (KIA), and the Indo-Pakistan Plate, bounded by the Main Karakoram Thrust (MKT) and Main Mantle Thrust (MMT) (Fig. 1). The Karakoram Block developed along the southern margin of the Asian Plate during the Late Permian-Triassic and is displaced from southern Tibet by the Karakoram Fault.

The Main Karakoram Thrust (MKT) is a Cretaceous to Tertiary suture zone separating the Karakoram Block (Asian Plate) from the Kohistan Island Arc, formed during arc continent collision and mélange development. The Kohistan-Ladakh Arc in the western Himalayas resulted from northward intra-oceanic subduction of Neo-Tethyan lithosphere beneath the Asian margin. The Main Mantle Thrust (MMT)/Indus Suture Zone marks the boundary between the Kohistan Arc and the Indian Plate, recording subduction and Tethyan Ocean closure, with arc emplacement onto the Indian Plate at ~50 Ma. The Nanga Parbat-Haramosh Massif reflects southward consumption of Proterozoic Indian crust beneath the arc system (Fig. 1).

The Hanzal Sarot Valley (Gilgit District) is a U-shaped valley within the Kohistan Island Arc, where the Main Karakoram Thrust trends NE-SW, separating the Karakoram Block from the arc. It lies within the Kohistan Batholith, which intruded the Thelichi and locally the Gilgit Formation. The area exposes plutonic (granite-granodiorite), metavolcanic (basalt-basaltic andesite), and metasedimentary (marble and Hanzal slate) rocks, with dominant multiphase plutons alongside subordinate Thelichi, Greenstone complex, and minor Gilgit Formation.

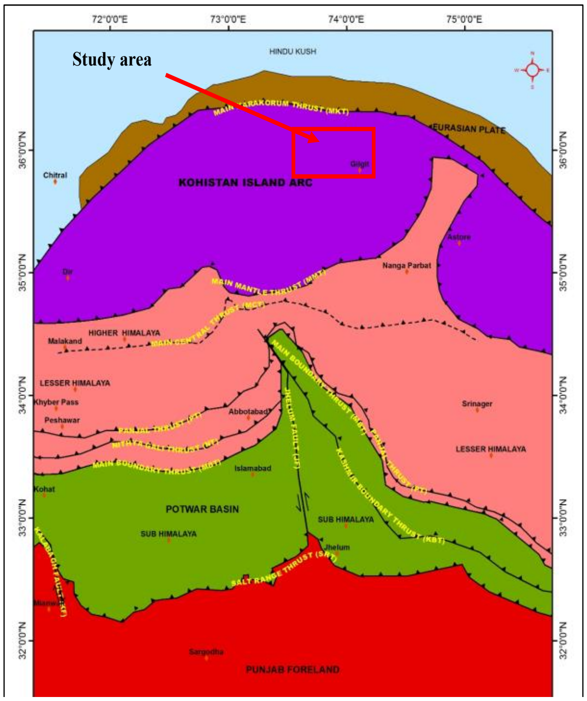

Fig. 1. Tectonic framework of Northern Pakistan (After Kazmi & Rana, 1982; Rustam & Ali, 1994; Chaudhry*et al*., 1997).

Materials and Methods

The study integrates field investigations, systematic sampling, and laboratory analyses. Geological mapping and sampling were conducted using a GPS (±8 m accuracy) to document lithology and mineralization, yielding 22 representative samples (8 granite, 2 hornfels, 2 quartz veins (Table 1), of which 10 were selected for whole-rock geochemistry (Table 3). Petrography was performed on thin sections at Institute of Geology, University of Azad Jammu and Kashmir under transmitted and reflected light to determine mineralogy, textures, deformation, and alteration (Table 2). Major and trace elements (Cu, Zn, Fe, Co) were analyzed by ICP-OES after HNO_3-HCl-HF digestion, with Ag by ICP-MS/AAS and Au by fire assay-ICP-MS/AAS at Shiraz University. Data quality was ensured using blanks, certified standards, duplicates, and limits defined by 3σ (detection) and 10σ (quantification), with recoveries of 85-110% and precision of <5% (major) and <10% (trace elements). Data processing and geochemical classification were performed using OriginPro 6.1 and OriginLab Pro 2024.

Results and Discussion

Field Observations

The Sarot Hanzal valley is comprised of volcanic to plutonic rock (rhyolite, granite and granodiorite). The granite body

Table 1. Field characteristics, alteration, and mineralization of rock units.

S. No.	Rock Type	Thickness (m)	Grain Size/ Texture	Color	Structural Features	Alteration Type	Mineralization / Ore Minerals	Field Description / Remarks
1	Granite	—	—	—	—	alteration	Pyrite, Chalcopyrite	Sulfide-bearing granite
2	Granite	—	—	—	—	Weak alteration	Galena	Sulfide-bearing granite
3	Granite	—	—	—	—	—	—	No significant features
4	Granite	—	Coarse-grained	—	Presence of xenolith	—	—	Indicates magma mingling
5	Boulder	—	Massive	Brownish	—	Oxidation (gossan-like)	Limonite, hematite, quartz	Surface weathering product
6	Vein	2–3	Massive vein	Green-blue	Vein structure	Hydro-thermal alteration	Azurite, malachite, sulfides	Cu-rich mineralization
7	Vein	0.76–0.91	Massive	—	—	—	—	Narrow mineralized vein
8	Vein	0.70–0.91	Massive	—	—	—	—	Similar to sample 7
9	Granite	—	—	—	—	—	Sulfide minerals	Disseminated mineralization
10	Vein	0.15–0.30	Massive	Reddish-brown	—	Oxidation	Hematite, limonite	Iron oxide-rich vein
11	Granite	—	—	—	Strike: N80°E, Dip: S80°E	—	—	Complex dip variation
12	Vein	—	Gossanous	Brownish	—	Strong oxidation (gossan)	Limonite, hematite, sulfides	Weathered sulfide zone
13	Granodiorite	—	Medium-grained	—	—	Argillic alteration	Azurite, malachite	Feldspar altered to clays
14	Granitic Body	—	—	—	—	—	—	No significant observation
15	Granitic Body	—	—	—	—	—	—	No significant observation
16	Altered Zone	—	—	Reddish-brown	—	Hematitization	Hematite	Oxidized alteration zone
17	Altered Zone	0.60–0.76	Massive	Black	—	Magnetite alteration	Magnetite	Fe-rich alteration
18	Granite	—	Coarse-grained	Greenish	—	Propylitic alteration	—	Chlorite/epidote alteration
19	Granite	—	Fine-grained	Greenish	—	Propylitic alteration	—	Chlorite/ epidotization
20	Granite	—	—	—	—	—	—	No detailed observation
21	Diorite/Tonalite	—	Fine–medium grained	Black to grey	—	Weak alteration	—	Mafic-intermediate intrusion
22	Granite	—	—	—	Shear zone; Strike N52°E, Dip 71°NW	Shearing + alteration	—	Structural control present

Petrographic and field data show that the Hanzal granitoids are mainly monzogranite to granodiorite, formed by fractional crystallization of hydrous intermediate to felsic magmas. Gabbroic and dioritic xenoliths indicate magma mixing and assimilation, suggesting complex magmatic evolution. Textures such as plagioclase zoning, myrmekite, and microfracturing record crystallization dynamics and post-emplacement tectonic deformation.

Mineralogically, the Hanzal Sarot granite consists of quartz (30-42%), plagioclase (15-25%), alkali feldspar (25-43%), muscovite (0-2%), biotite (1-3%), opaque minerals (1-12%), hornblende (1-4%), amphibole (0-1%), apatite (0-1%), rutile (0-1%), chlorite (0-1%), cordierite (0-1%), and zircon (0-1%) (Table 2), and based on IUGS QAP ternary classification (Fig. 4). These compositions plot within the granite field, corresponding to monzogranite and granodiorite, reflecting the regional geological setting, while observed mineralogical variations in some rock bodies are attributed to post-collisional alteration associated with Indian-Asian plate convergence.

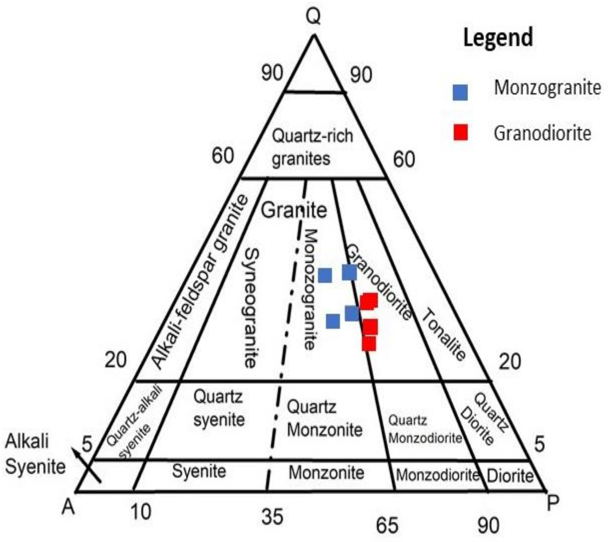

Fig. 4. Plots of modal mineralogy of granite from the Hanzal-Sorat area in Streckeisen's (1974) QAPF classification diagram for plutonic igneous rocks.

Geochemistry

The granitoids exhibit crustal-melting signatures consistent with syn- to post-collisional emplacement in a convergent margin setting. Mineralization is structurally controlled and spatially associated with quartz veins and hornfels, where Cu-Pb sulphide assemblages (chalcopyrite, galena, sphalerite, chalcocite) occur along fractures and recrystallized quartz domains. Multiple hydrothermal pulses related to successive magmatic events, combined with compressional deformation, facilitated fluid migration and ore deposition, while supergene processes overprinted primary mineralization, producing secondary Cu minerals such as malachite and azurite.

Quartz veins (white to chocolate brown) host dominant ore mineralization, including chalcocite, pyrite, and chalcopyrite, with hematite, limonite alteration zones and malachite, azurite staining indicating oxidation and secondary enrichment. Supergene processes formed chalcocite through alteration of primary sulphides via meteoric fluids in the enrichment zone, whereas hypogene mineralization reflects hydrothermal (ascending fluid) activity typical of mesothermal systems. Hornfels shows fine-grained assemblages dominated by plagioclase, biotite, quartz, pyroxene, and opaque minerals, with strong sericitization of plagioclase and accessory zircon, sphene, and tourmaline, indicating intense fluid-rock interaction. Quartz commonly exhibits fracturing, recrystallization, and inclusion-filled fractures by opaque ore minerals.

ICP-OES results reveal low to moderate Cu (0.000081-0.001118%) and Pb (0.001128-0.868%), with minor Zn, Fe, Ag, Au, and Co. Although anomalous, Cu grades are below economic ore thresholds (~1-2.5% Cu), indicating sub-economic but geochemically significant mineralization.

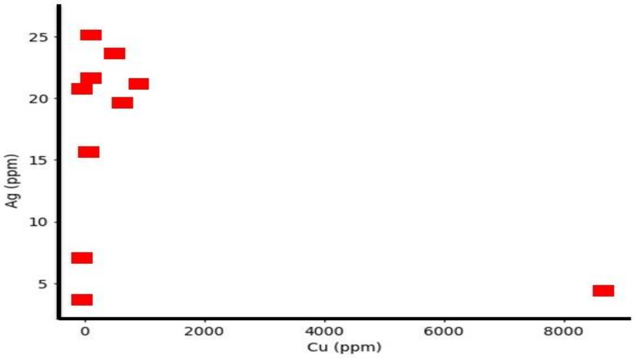

Fig. 5. Diagram for Hanzal quartz veins showing weak correlation and dispersion, reflecting magmatic-hydrothermal metal fractionation via brine-vapor separation and fluid evolution (Heinrich *et al*., 1999; Sillitoe, 2010).

Metal Correlations

The Cu-Au plot (Fig. 5) shows a weak to moderate positive correlation with scatter, indicating a magmatic hydrothermal (porphyry) system. Cu-Au co-enrichment reflects a common magmatic source, while dispersion results from fluid phase separation, brine vapor immiscibility, and metal fractionation during evolution of the hydrothermal system (Heinrich *et al*., 1999; Richards, 2011). Cu-rich outliers likely represent early high-salinity brines at depth, whereas Au-enriched samples reflect later, cooler, and more dilute fluids during ascent and mixing. Overall, the pattern defines vertical metal zonation from Cu-dominant core to Au-enrichedupper levels, consistent with a porphyry-epithermal continuum linked to a fertile arc-related intrusion (Sillitoe, 2010).

Table 2. Mineralogical model showing the composition of granite, quartz vein and hornfels.

Model Composition	QS-1	QS-6	S-7 (Hornfels)	S-8 (Hornfels)	GS-4	GS-9	GS-11	GS-13	GS-18	GS-19	GS-21	GS-22
Quartz	89	90	5	8	40	35	32	37	42	30	34	35
Plagioclase	-		20	22	20	15	18	15	16	20	25	20
Orthoclase	-				15	20	22	25	20	23	25	20
Perthite	-				10	15	18	12	10	20	8	15
Biotite	1	1	25	20	2	3	1	1	2	1	1	1
Hornblende	-				2	1	4	2	3	1	2	3
Rutile	-				1	1		1				
Apatite	-				1		1	1	1			1
Zircon	-				1	1		1	1	1	1	
Opaque mineral (ore mineral)	9	7	30	25	6	6	2	2	2	2	1	12
Amphibole							1	1				
Chlorite	1		1	3	-	1			1	1	1	1
Sericite	-		16	20	-						1	
Cordierite	-		1	1	-	1			1			
Muscovite	-	2	2	1	2	1	1	2	1	1	1	1
Total	100	100	100	100	100	100	100	100	100	100	100	100

Table 3. Trace element concentration in the different samples.

Sample Name		S-01	S-02	S-03	S-06	S-7	S-8	S-11	S-13	S-15	S-17
Cu	PPM	98.1	33.72	11.28	21.1	24.56	33.36	969	8684	340.96	357
	%age	0.00981	0.003372	0.001128	0.00211	0.002456	0.003336	0.096	0.868	0.034096	0.0357
Pb	PPM	0.81	9.74	9.54	2.53	5.83	11.18	ND	ND	ND	ND
	%age	0.000081	0.000974	0.000954	0.000253	0.000583	0.001118	ND	ND	ND	ND
Zn	PPM	10.53	20.3	17.46	13.56	0.69	2.43	12.07	12.81	11	7.41
	%age	0.001053	0.00203	0.001746	0.001356	0.000069	0.000243	0.001207	0.001281	0.0011	0.000741
Ag	PPM	21.82	2.66	6.97	20.84	15.56	24.86	20.3	1.94	23.53	19.31
	%age	0.002182	0.000266	0.000697	0.002084	0.001556	0.002486	0.00203	0.00194	0.002353	0.001991
Au	PPM	3.17	2.57	8.38	11.78	24.93	22.16	8.86	1.67	2.75	7.9
	%age	0.000317	0.000257	0.000838	0.001178	0.002493	0.002216	0.000886	0.000167	0.000275	0.00079
Fe	PPM	3.3	0.29	2.16	2.77	3.98	3.78	3.58	0.5	1.64	2.65
	%age	0.00033	0.000029	0.000216	0.000277	0.000398	0.000378	0.000358	0.00005	0.000164	0.000265
Co	PPM	40.6	61.17	36.3	43.13	101	105	101	15.19	92.21	50.47
	%age	0.00406	0.006117	0.0353	0.004313	0.0101	0.0105	0.0101	0.001519	0.009221	0.005047

The Cu-Ag plot (Fig. 6**)** shows weak correlation with strong dispersion**,** indicating metal decoupling in a magmatic-hydrothermal system**.** Ag enrichment at low-moderate Cu reflects intermediate to distal hydrothermal conditions, whereas the Cu-rich, Ag-poor outlierrepresentsproximal, high-temperature brine-dominated mineralization. This pattern indicates fluid evolution, phase separation, and vertical metal zonation typical of porphyry-epithermal systems (Sillitoe, 2010; Heinrich *et al*., 1999).

The Cu-Pb plot (Fig. 7) shows weak correlation and significant scatter, indicating decoupled metal behavior in a magmatic-hydrothermal system. Cu enrichment reflectshigh-temperature, proximal brine-dominated mineralization**,** whereas Pb is associated with lower-temperature, distal to late-stage fluids. The Cu-rich, Pb-poor outlier represents a proximal core signature**,** while the remaining data indicate metal zonation typical of a porphyry-epithermal system (Sillitoe, 2010; Heinrich *et al.*, 1999).

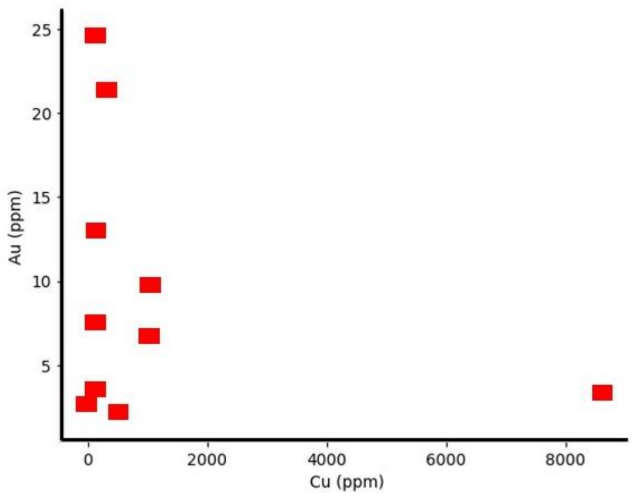

Fig. 6. Diagram showing weak correlation and dispersion, reflecting hydrothermal fractionation and metal zonation (Heinrich *et al*., 1999; Sillitoe, 2010).

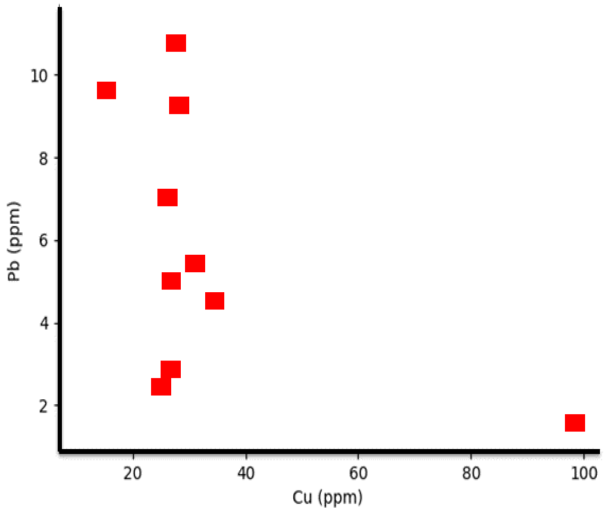

Fig. 7. Diagram showing weak correlation and metal decoupling, reflecting hydrothermal fractionation and zonation (Heinrich *et al*., 1999; Sillitoe, 2010).

The Hanzal granitoids exhibit mineralogical and geochemical characteristics consistent with fertile, hydrous, and oxidized calc-alkaline magmas typical of arc-related metallogenic systems. Petrographic features, including oscillatory zoning in plagioclase, myrmekitic intergrowths, and the presence of mafic xenoliths (Fig. 3), indicate open-system magmaticevolution involving magma mixing, assimilation, and fractional crystallization. These processes are widely recognized as fundamental mechanisms controlling metal enrichment in arc magmas (Richards, 2011, 2015). Recent studies emphasize that magmatic fertility is governed not only by bulk composition, but also by volatile content (H_2O-S-Cl) and oxidation state, which control metal solubility and transport efficiency (Wilkinson, 2013; Loucks, 2014; Zhao *et al*., 2022).

The occurrence of hydrothermal alteration assemblages (sericite and chlorite) and sulfide-bearing quartz veins at Hanzal suggests that the parental magma was volatile-rich and sulfur-bearing**,** facilitating efficient transport of copper and associated metals as chloride complexes. Moreover, the tectonic evolution of the Kohistan arc, characterized by crustal thickening and prolonged magmatic activity during continental collision**,** likely promoted extended magma residence times and volatile accumulation. Such conditions are increasingly recognized as critical for the development of porphyry-type mineral systems (Hou *et al*., 2017; Chiaradia, 2020). Therefore, the.Hanzal granitoids represent a fertile magmatic system, even though surface mineralization appears limited in scale.

The spatial association between granitoids and Cu-Pb mineralization (Fig. 2) indicates a direct genetic relationship between magmatic evolution and hydrothermal processes**.** Ore-forming fluids were likely exsolved during late-stage crystallization, consistent with established models of magmatic fluid saturation and phase separation (Heinrich *et al*., 1999; Kuzmanovic & Pokrovski, 2012). Field relationships and petrographic evidence, including fracture-controlled quartz veins, sulfide infilling, and multiple generations of veining, indicate that mineralization developed within a pulsatory hydrothermal system rather than a single continuous event.

This interpretation is supported by modern models proposing that porphyry systems evolve through episodic magma recharge and transient fluid release, resulting in cyclic pressure fluctuations and repeated mineralization events (Richards, 2015; Weis *et al*., 2022). The weak to moderate correlations between Cu, Au, Ag, and Pb (Figs. 5-7) further reflect metal fractionation during fluid evolution, driven by cooling, depressurization, and fluid-rock interaction. These processes result in metal decoupling and geochemical dispersion, characteristic of evolving magmatic, hydrothermal systems (Heinrich *et al*., 1999; Sillitoe, 2010).

Structural features exert a primary control on mineralization at Hanzal. Quartz veins and mineralized zones are aligned along consistent fracture orientations (Table 1), demonstrating that tectonic structures acted as principal pathways for hydrothermal fluids**.** The interaction between magmatic overpressure and regional stress fields likely generated fracture networks that facilitated fluid migration and metal deposition.

These include extensional fractures that enhanced permeability, shear zones that focused fluid flow, brecciated zones that promoted fluid-rock interaction. Structural control is a fundamental feature of porphyry and epithermal systems, where permeability architecture governs fluid flow and ore deposition (Sillitoe, 2010; Richards, 2015). Accordingly, the Hanzal system is best interpreted as a tectono-magmatic system, in which magma acts as the primary source of metals and fluids, while structural frameworks regulate their transport and localization.

Geochemical relationships (Figs. 5–7) indicate significant dispersion and weak correlations among metals, reflecting metal zonation and progressive hydrothermal evolution**.** The observed distribution suggests copper enrichment in proximal, high-temperature zones, lead and zinc enrichment in intermediate zones, and gold and silver enrichment in distal or late-stage environments. This pattern is consistent with porphyry–epithermal transition systems, where metal distribution is controlled by temperature, pressure, and fluid composition (Simmons et al., 2005; Sillitoe, 2010). Recent studies highlight the importance of fluid phase separation (brine–vapor immiscibility) in controlling metal partitioning, particularly for copper and gold (Heinrich et al., 1999; Kouzmanov & Pokrovski, 2012). The dispersion observed in Hanzal data supports this mechanism, indicating that multiphase fluid evolution played a critical role in ore formation**.**

The presence of malachite, azurite, and chalcocite (Fig. 2) indicates significant supergene alteration and secondary enrichment**,** resulting from oxidation of primary sulfide minerals. These processes involve meteoric water infiltration, oxidation, and downward migration of metal-bearing solutions. Supergene enrichment can substantially enhance copper grades, particularly in uplifted arc environments (Sillitoe, 2010; Reich et al., 2020). At Hanzal, such processes likely contributed to localized enrichment, although they may also obscure primary mineralization patterns.

The Hanzal system exhibits key features characteristic of intrusion-related and porphyry-style mineral systems**,** including: calc-alkaline, oxidized magmatism, multiphase intrusion history, structurally controlled hydrothermal mineralization, distinct metal zonation, and supergene overprinting Although average copper concentrations are relatively low (<1%), the presence of localized high-grade zones (up to 0.868% Cu; Table 3) suggests that the exposed mineralization may represent the upper or peripheral portion of a larger, concealed system. This interpretation is consistent with global observations, where surface expressions commonly represent distal parts of deeper porphyry systems (Richards, 2015; Chiaradia, 2020).

Conclusion

This study provides new insights based on integrated field, petrographic, and geochemical investigations. The Hanzal granitoids are interpreted to have originated from hydrous, oxidized magmas derived from a subduction-modified crustal source, with their evolution controlled by magma mixing, assimilation, and fractional crystallization processes. Copper-lead mineralization is genetically associated with late-stage magmatic fluid exsolution, where hydrothermal fluids migrated through structurally controlled pathways and precipitated sulfide minerals within quartz veins and along contact zones. Geochemical evidence further indicates progressive metal zonation and hydrothermal evolution governed by decreasing temperature, pressure variations, and fluid phase separation, consistent with porphyry, epithermal transition systems. Structural controls played a fundamental role in focusing fluid flow and localizing ore deposition, emphasizing the importance of tectonic architecture in the mineralization process. In addition, supergene processes overprinted the primary mineralization, leading to local enrichment and enhancement of near-surface copper grades.

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