Geochemical associations of gold mineralization at Okzhetpes ore field

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Abstract. The rank correlation coefficient was meticulously calculated, revealing significant correlations between elements in geochemical sections and levels of ore occurrences in different areas. These calculations were based on the comprehensive results of assay and spectral analyses for 12 chemical elements of 291 samples from ore zone No. 2 and 500 samples from ore zones No. 3 and No. 5. The gold-bearing rocks of ore zones 3 and 5 are intricately associated with the distribution of sedimentary-diagenetic pyrite layers, which, along with the host rocks, played a crucial role in the dissolution and cataclasis in the formation of veins and veins of quartz. The sedimentary origin of pyrite in the Okzhetpes ore field is strongly supported by its geochemical features. It is established that at an average gold content in pyrite at the level of 5-7 g/tons, only this mineral provides up to 10 clark concentrations for the whole rock: Au, Ag, Se, Cu, As. Notably, some differences in the correlation of noble metal contents in samples from ore zone 2, localized predominantly in carbonate rocks, and ore zones 3 and 5 in tuffogenic sandy shale, where a closer relationship between arsenic and tungsten and molybdenum is clearly indicated.

1 Introduction

Understanding the processes that govern mineralization and ore formation is crucial in economic geology and resource management [1]. Across various geological settings, the interplay of geochemical, mineralogical, and tectonic factors leads to the concentration of economically valuable elements, forming the basis for mining and extraction industries. In particular, sedimentary-hosted and hydrothermal gold deposits have drawn considerable attention due to their complex formation mechanisms and economic significance [2]. These deposits often feature an intricate association of minerals, such as pyrite, which plays a pivotal role in the enrichment and distribution of noble metals within ore zones.

Pyrite, a common sulfide mineral, is especially important in sedimentary and diagenetic environments where it acts as a host for metals such as gold, silver, and arsenic [3]. In these environments, the geochemical characteristics of pyrite, along with its formation history, provide valuable insights into mineralization processes. Research into the sedimentary-diagenetic origins of pyrite has shown that such minerals can exhibit high concentrations of gold and associated elements, driven by both primary sedimentary conditions and subsequent hydrothermal alterations [4]. This

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dual influence underscores the complexity of pyrite-hosted gold systems, making them of particular interest for exploration and extraction strategies.

The Okzhetpes ore field presents a distinctive case for studying sedimentary-hosted mineralization [5]. This region, with its diverse lithological composition, exhibits significant gold occurrences and other trace elements associated with pyrite-rich zones. These ore zones reveal correlations between various geochemical elements, offering insights into the sedimentary and diagenetic factors contributing to metal enrichment [6]. The specific relationships between these elements within the ore zones suggest distinct pathways of mineralization, which may be influenced by the underlying lithology and structural conditions unique to each zone [7].

This study seeks to explore the geochemical features of pyrite and associated elements within the Okzhetpes ore field to better understand the mineralization processes at play. By investigating the elemental associations and distribution patterns, this research aims to clarify the role of sedimentary-diagenetic processes in shaping mineral deposits in this region, contributing to broader efforts in mineral resource assessment and exploration in sedimentary-hosted ore systems.

2 Materials and methods

Field sampling was conducted across three primary ore zones within the Okzhetpes ore field, targeting areas with known gold occurrences and pyrite-rich zones. Samples were collected systematically to represent both the lithological diversity of the zones and the spatial distribution of mineralization features. Each sample was carefully labeled, transported to the laboratory, and prepared for geochemical analysis through drying, crushing, and sieving to obtain a uniform particle size.

A comprehensive suite of assay and spectral analyses was performed to determine the concentration levels of 12 chemical elements associated with gold mineralization and sedimentary-diagenetic processes. Analytical techniques such as atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS) were utilized to achieve precise measurements of metal concentrations, particularly for noble metals and trace elements. The focus was on elements commonly associated with pyrite-hosted gold systems, including gold (Au), silver (Ag), arsenic (As), copper (Cu), selenium (Se), and other trace metals.

To investigate inter-element relationships and assess the association between mineralization and lithology, rank correlation coefficients were calculated. This statistical approach allowed for the detection of significant correlations among elements within each ore zone, shedding light on potential co-enrichment patterns and the geochemical controls on metal distribution. Rank correlation was chosen for its robustness in handling non-linear relationships, which are common in mineralized systems with complex depositional histories.

Detailed mineralogical analysis of pyrite and host rocks was conducted using optical microscopy and scanning electron microscopy (SEM). These methods provided insights into the textural features and compositional variations within pyrite grains, which are critical in understanding the mineral's role in hosting gold and associated elements. Petrographic studies focused on identifying alteration patterns and examining the mineral assemblages associated with gold occurrences, such as quartz and other sulfide phases.

3 Results and discussion

The systematic and rigorous study of the Okzhetpes ore field in the Bukantau Mountains commenced in 1974. The gold (Barkhanny) and silver (Okzhetpes) deposits are strategically located within its boundaries. In recent years, we have identified and meticulously studied ore concentrations of gold in zones 2, 3, and 5. To determine the correlation between the elements in geochemical sections in different areas and levels of ore occurrences, we employed the rank correlation coefficient. These calculations were performed on the comprehensive assay results and spectral analyses for 12 chemical elements, 291 samples for ore zone № 2, and 500 samples for ore zones № 3 and № 5. The critical value of the correlation coefficient at a 5% significance level is 0.13 and 0.15, respectively, further underscoring the thoroughness of our research.

A.A.Rubanov [7] briefly characterized 11 mineral complexes for the Bukantau Mountains. Specific deposits and ore occurrences in Bukantau confirmed the industrial significance of manifestations of coal-gold-sulfide, gold-sulfide-quartz, rare-metal-gold-quartz, gold-polysulfide-silver-quartz, gold-copper-coalescence mineral complexes. None of their manifestations is sterile to gold, tungsten, or silver, as it is typical for gold deposits in black shale strata of Tamdytau, Beltau, and Nuratau.

The Okzhetpes ore field exhibits a complex geological structure, encompassing a variety of sedimentary, metamorphic, and intrusive formations that provide a unique context for mineralization, especially in gold-bearing ore zones. This geological diversity plays a significant role in shaping the mineralogical characteristics and distribution patterns within the field, and its stratigraphy offers valuable insights into the processes underlying gold deposition.

At the core of the Okzhetpes ore field are sedimentary-metamorphic formations, particularly from the Kokpatass Formation, which includes carbonate deposits from the middle to upper Devonian and extends into the lower and middle Carboniferous periods. The presence of carbonate sediments is critical, as they frequently serve as hosts for mineral deposits, providing suitable environments for mineralization through processes such as fluid interaction and diagenesis. The carbonate strata in the Okzhetpes Formation, labeled as D2-3oc, are central to the field's geological profile, forming a stable platform for various mineralization processes. This formation is largely composed of limestones and dolomites, which are favorable to the development of mineralization structures, including quartz veins and sulfide concentrations. Such characteristics make it a prime target for understanding gold accumulation and associated element distributions within the ore zones.

Surrounding the carbonate core, the Okzhetpes ore field is delineated by the West Oktogetpes Formation, particularly on its northern and western boundaries. This formation is characterized by a range of lithologies, including phyllite-like coal-quartz shales, sandstones, siltstones, siliceous shales, microquartzites, and lenses of dolomites and limestones. The lithological diversity within the West Oktogetpes Formation is of particular interest as it presents a highly variable mineralogical environment. Additionally, the formation contains layers of andesite and andesidacite metatuffs, with a total stratigraphic thickness reaching approximately 450 meters. These metatuffs, altered volcanic rocks rich in fine-grained mineral phases, contribute to the geochemical complexity of the region and are integral to the localized mineralization patterns observed in the gold ore zones 3 and 5. These ore zones exhibit distinct mineralogical associations and structural characteristics that reflect both the primary depositional environment and subsequent hydrothermal alterations.

The structural complexity of the Okzhetpes ore field is further amplified by the presence of the Kpatas Formation, which forms part of the “basement” of the Okzhetpes uplift. This formation, marked by metamorphic and plutonic rocks, lies beneath the overlying sedimentary layers, contributing to the structural stability and geological evolution of the ore field. The Kpatas Formation includes highly deformed rocks with indications of tectonic activity, which may have provided conduits for mineralizing fluids. Such tectonic features can enhance permeability, allowing mineral-rich fluids to migrate and deposit metals within favorable host rocks. In this context, the formation represents a foundational component of the Okzhetpes uplift, influencing both the spatial distribution of mineralized zones and the geochemical interactions among various lithological units.

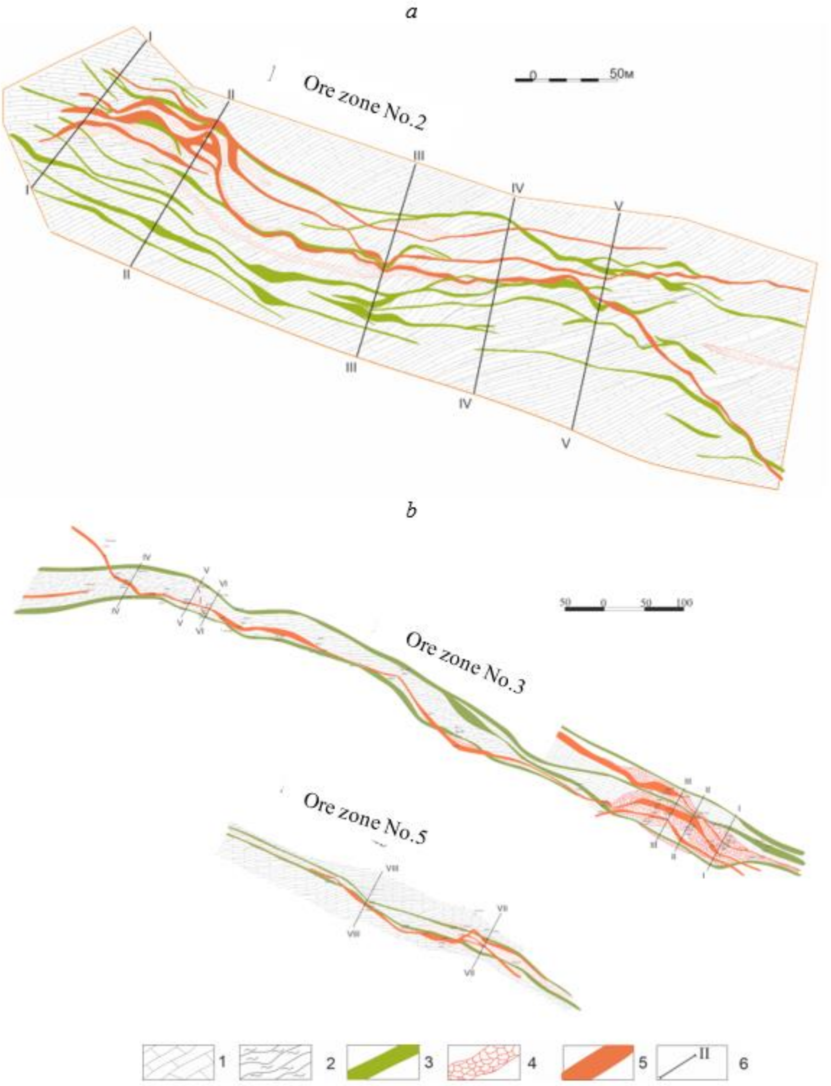

Fig. 1. Correlation of ore zones No.2 (a), No.3, and No.5 (b) with belts of lamprophyre dykes and diorite porphyrites at the Okzhetpes ore field. 1 - limestones; 2 - shales; 3 - lamprophyres and diorite porphyrites; 4 - crushing zones; 5 - ore zones; and, 6 - exploration lines and their numbers.

Intrusive activity within the Okzhetpes ore field is represented by a dyke complex comprising granodiorites, granodiorite porphyrites, syenogranodiorite porphyries, and other porphyritic rocks closely associated with the Kokpatas complex. These intrusive rocks play a significant role in the geodynamic evolution of the ore field, providing heat and chemical components necessary for hydrothermal alteration and ore deposition. The dykes cut through the sedimentary formations, introducing both magmatic fluids and thermal energy that drive the remobilization and concentration of metals, particularly within gold-bearing zones. Such intrusions are often associated with gold and sulfide mineralization, where the interaction between magmatic and sedimentary/metamorphic fluids can create complex geochemical environments favorable to metal precipitation.

Among the intrusive units, lamprophyre dykes are prominent, with spessartites—characterized by intense chloritization—being particularly common. Lamprophyres are typically rich in volatile elements and can create zones of metasomatic alteration, contributing to the mineralogical diversity of the field. The chloritization observed within spessartites indicates significant fluid interaction, as chlorite often forms in response to hydrothermal alteration. However, the spatial, material, and genetic relationships of these lamprophyres to the ore deposits in the Okzhetpes field remain somewhat ambiguous, as they exhibit inconsistent associations with the mineralized zones. In some instances, these dykes are closely associated with mineralization, while in other areas, their connection appears less direct, possibly due to differences in fluid flow patterns or variations in the composition of the mineralizing fluids.

Gold-bearing rocks of ore zones 3 and 5 are associated with the distribution of sedimentary-diagenetic pyrite layers in them, which participated together with the host rocks in the stratification and cataclasis in the formation of veins and veins of quartz, dyke intrusion, as it happened at other gold objects in the black shale strata of the Central Kyzylkum. At the Okzhetpes ore field, the most common are nodule layers and lumpy and crystallographic idioblasts of pyrite (Fig. 2).

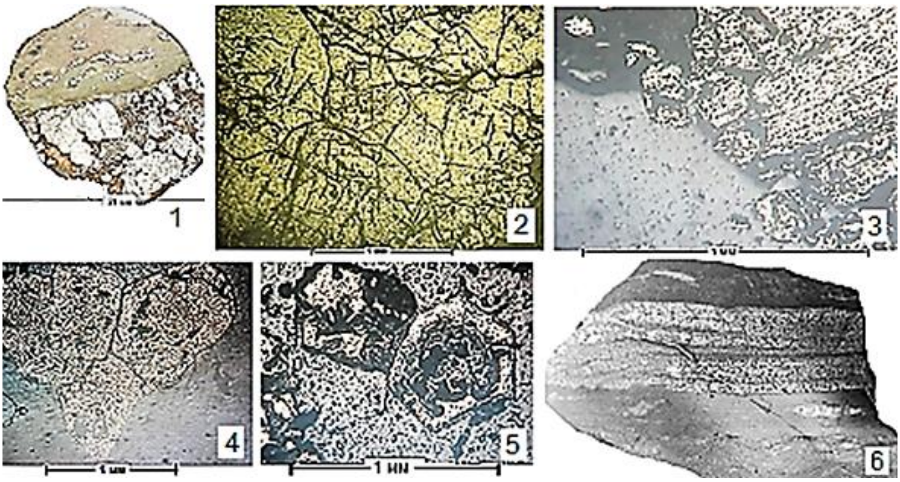

Fig. 2. Forms of manifestation of sedimentary-diagenetic pyrite in rocks of ore zone 3. 1 - view of an intensively catalyzed layer of spongy pyrite in andesitic tuff. 2 - intensive cataclasis of pyrite layer (detail of photo 1). 3 - cataclasis of stratified pyrite puff during rock occlusion. 4, 5 - idioblastic crystals of sponge pyrite in andesitic tuff. 6 - lenticular and puffed outcrops of spongy pyrite in tuffs of Turbay deposit; fulfillment of the fracture by pyrite only at the intersection of the pyrite puff. Polished slits and stufa.

Globular microconcretions 0.005-0.2 mm in diameter, lenticular and rounded macroconcretions are more common in ores and host rocks of Kokpatas and Daugyztau deposits. They are also widespread in the ores of the Kumtor and Sukhoi-Log deposits [3, 8]. Along with them, macrocretionary pyrite layers are widespread at the same objects. The pyrite content of such forms in the rocks of ore zone 3 varies from 1 to 5%; there are also layers with more abundant extractions (Fig. 3 and 4).

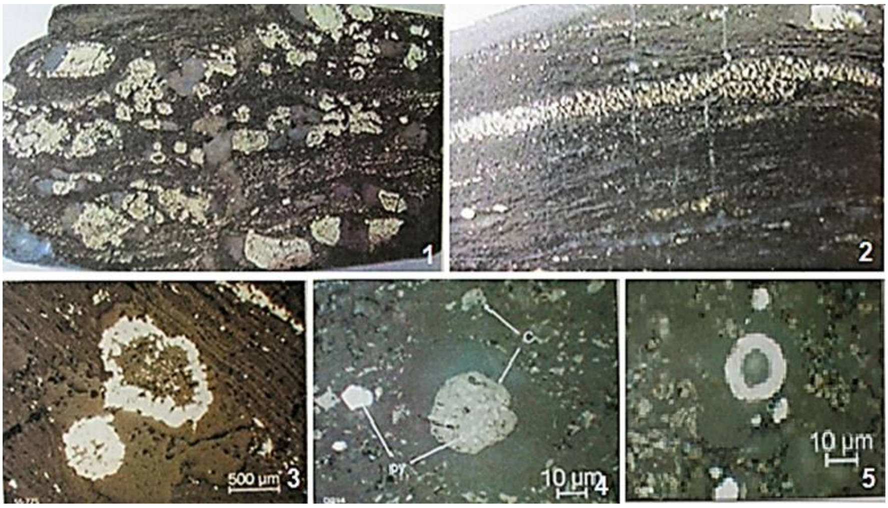

Fig. 3. Sedimentary-diagenetic pyrite in rocks and ores of the Kumtor deposit. 1-2 - layered distribution of nodules; 3-5 - pyrite framboids in chalcedony rims with melnikovite in the center. The gold content in such pyrite reaches 1400 g/t.

Fig. 4. Globular nodules of marcasite in Paleogene sandstones and siltstones of the Egerbelitau are composed of small globules. From materials of A.N.Smirnov. In the composition of this concentrate were found, g/t: Ag - 45, Pb - 660, Bi - 170, Zn - 90, Cu - 175, Co - 170, Ni - 94,0, Rb - 60, W - 530, Mn - 2380, Ti - 550, Fe - 38,0, K - 2500 (X-ray fluorescence determinations of V.A.Bannov). Mass-spectrally additionally revealed, g/t: As - 150.0, Se - 4.2, Te - 0.54, Tl - 5.0.

Regional and/or local development of sericitization of especially fine-grained rock varieties pigmented with bioorganic carbonaceous matter indicates the activation of potassium mobility already at the initial stages of greenschist meta-erosion. Feldspar sericitization is an exothermic reaction [2, 9]:

$$4KAlSi_3O_8 + 4H_2O \rightarrow Al_4[Si_4O_{10}](OH)_8 + 2K_2SiO_3 + 6SiO_2 + 56\ \text{kcal}$$

Possibilities of sedimentary gold-bearing pyrite formation are widely covered in the geological literature. In this case, iron abundance in volcanogenic-sedimentary derivatives of andesibasaltoid magmas and hydrogen sulfide generation by sulfate-reducing microorganisms in sediments enriched with bioorganic carbonaceous matter are fundamentally important [1, 6, 9]. Simplistically, the birth of sedimentary pyrite is described by the following reactions:

$$H_2SO_4 + 2C \rightarrow H_2S + 2CO_2 \quad \text{and } 2Fe(OH)_3 + 4H_2S \rightarrow FeS_2 + 4H_2O + O_2 + 104{,}66\ \text{kcal}$$

Both reactions are exothermic. Gold in seawater is present in the form of stable gold-chloride complexes [8, 10], the saturation solubility of which is characterized by values of 10-10-10-11%; for gold sulfides, it ranges from 10-16 to 10-19%. This means that with the appearance of hydrogen sulfide in water, almost all gold from seawater will settle with sulfides. Silver, even if leached in some way from sedimentary material, will be converted into a solid phase by chlorine here, i.e., it does not get a chance to migrate and accumulate in the zones of the sea basin with hydrogen sulfide contamination of water.

The role of bioorganic carbonaceous matter in the enrichment of rocks with sulfides is clearly emphasized by the presence of globular concretions of marcasite in the Paleogene red-colored strata of the Bukantau only in rare layers of dark gray silty-clayey rocks. Lumpy and spherical macroconcretions of marcasite in brown coal of the Angren and Moscow basins are widespread. Only bioorganic sulfate-reducing microorganisms generating hydrogen sulfide can develop in sediments only in the presence of bioorganic sulfate.

The sedimentary origin of the described pyrite forms at Okzhetpes ore field is evidenced by their geochemical features. It is established that at the average gold content in pyrite at the level of 5-7 g/t, only this mineral provides up to 10 clark concentrations for the whole rock: Au, Ag, Se, Cu, As (Table 1). The practical absence of a pair correlation between gold and silver contents and other metals was noted (Table 2). There are some differences in the correlation of noble metal contents in samples from ore zone 2, localized mainly in carbonate rocks, and ore zones 3 and 5 in tuffogenic sandy shale, where a closer association of arsenic with tungsten and molybdenum is indicated. Tungsten, molybdenum, and arsenic easily ally with silicon in quickly migrating heteropolyacids, especially at increased activity of alkali metals [8-10].

The weakened correlation of gold and silver contents (its practical absence) in ore-bearing rocks is connected with their relations with chlorine, which is the main component in the anionic complex of seawater: gold gets migration mobility with it in the dissolved state, silver is precipitated by it. Therefore, pyrite is one hundred times richer in gold than the rock containing it (see Table 1). At the same time, silver is concentrated in the mineral, and rock is practically at the same level - tens of g/t. Ore Zone 2 is adjacent to the Okzhetpes silver ore deposit, but silver does not correlate with arsenic. Copper in Zone 2 correlates positively with almost all metals, while in Zones 3 and 5, only with silver, arsenic, molybdenum, and vanadium.

Table 1. Contents (g/t) of some chemical elements in rocks of ore zone 3 and concentrates of sedimentary-diagenetic pyrite from them.

Samples	**Rocks with pyrite efflorescence**				**Pyrite concentrate from these rocks**						**Average***
	PDGO-1p	**PDGO -2p**	**PDGO -3p**	**PDGO -4p**	**3/20-1**	**3/20-2p**	**3/20-3p**	**3/20-4p**	**3/20-5p**	**3/20-19p**	
Au	<05	<05	<05	<05	2.47	15.15	9.57	3.32	3.68	5.28	6.57
Ag	99.9	39	9.62	55	38.3	56.7	56.8	54.9	50.5	205	773
Cu	982	1470	1439	379	776	769	738	692	628	4349	1325.3
Ni	113	143	154	70.7	38.4	37.5	36.1	38.8	38.5	95.9	47.53
Co	7.81	102	127	16.6	7.81	192	145	144	115	20.5	1045
Mo	22.2	35.8	15.5	10.3	6.74	6.50	17.5	7.45	5.94	12.9	9.51
As	2175	3630	3516	2242	4347	3864	3220	3053	2055	8787	4221
Sb	69	30.8	48.5	57.2	19.5	20.7	11.6	11.6	10.4	141	35.8
Zn	47.2	256	336	91.3	45.4	47.4	37.9	33	34.9	162	60.1
Pb	43.4	43.5	59	47.5	35.8	31.3	30.8	26.7	24.2	153	50.3
Bi	2.88	7.11	7.79	2.16	11.4	11.2	6.91	7.43	6.43	11.9	9.21
Tl	070	082	059	094	<01	094	068	048	<01	0.61	0.14
Se	171	2624	1588	209	5333	5296	194	214	184	1.1	1870.3
Te	<0.30	3.51	1.80	1.17	3.15	2.61	5.76	6.84	4.32	0.90	3.93
Mn	63.5	183	193	103	33.5	23.2	47.1	21.6	17.6	62.5	34.25
Cr	87	250	206	68.7	29.1	33.8	30.1	26.1	40.7	96	42.63
V	9.92	78.5	100.1	13.1	10.4	4.69	8.40	6.61	8.82	7.22	7.69
Ti	58.5	45.7	58.9	54	31.5	25.4	29.3	18.7	23.5	39	27.9

Note. *Average** – average content in 6 pyrite concentrates.

The analysis reveals a notable lack of pair correlation between gold and silver contents with other metals, suggesting that the accumulation of these noble metals may occur independently of other elemental associations within the studied ore zones (Table 2). This absence of correlation implies distinct mineralization processes or fluid compositions responsible for the deposition of gold and silver, possibly indicating that they are controlled by factors unique to their geochemical environment.

Further analysis shows variation in the geochemical associations between ore zones. Specifically, ore zone 2, primarily hosted in carbonate rocks, demonstrates a different correlation pattern compared to ore zones 3 and 5, which are predominantly situated within tuffogenic sandy shale formations. In these tuffogenic zones, arsenic displays a closer association with tungsten and molybdenum, suggesting that the mineralizing fluids or depositional environments in these areas may favor the concurrent deposition or enrichment of these elements. This relationship points to a possible influence of lithology on metal distribution, where the porous, reactive nature of tuffogenic sandy shale may facilitate the transport and co-deposition of certain trace elements like arsenic, tungsten, and molybdenum.

The contrasting correlation patterns in these ore zones underline the role of lithological differences in shaping geochemical associations, where carbonate and tuffogenic sandy shale formations each present distinct mineral-hosting capacities and chemical affinities. Such differences have implications for mineral exploration, as they highlight the need for targeted approaches that consider both lithology and the specific elemental affinities within each ore zone.

Table 2. Pairwise correlation coefficients of metal concentrations in ore zones 2, 3, and 5 of the Okzhetpes ore field.

	Au	**Ag**	**Cu**	**Pb**	**Zn**	**As**	**Ni**	**Mn**	**Mo**	**W**	**Co**	**V**
Ore zone 2; 291 samples; significance level - 0.15												
Au		0.18	**0.24**	-0.03	-0.14	-0.13	-0.14	-0.19	**-0.31**	**-0.31**	**-0.20**	-0.02
Ag	-0.08		-0.01	0.10	**0.33**	-0.01	0.02	0.003	**0.32**	-0.02	0.00	0.02
Cu	0.01	**0.37**		**0.24**	**0.43**	**0.47**	**0.42**	**0.56**	**0.55**	**0.60**	**0.46**	0.03
Pb	0.09	0.23	0.02		**0.29**	0.10	0.14	**0.27**	**0.22**	**0.20**	0.11	0.01
Zn	0.13	0.23	0.03	**0.44**		0.15	**0.54**	**0.25**	**0.59**	**0.49**	**0.55**	0.02
As	**0.34**	**0.47**	**0.30**	**0.35**	**0.31**		0.15	**0.45**	**0.34**	**0.32**	0.19	0.01
Ni	0.12	0.01	0.05	**0.11**	**0.64**	**0.18**		0.17	**0.51**	0.16	0.80	0.02
Mn	-0.13	0.03	0.07	0.06	0.08	0.00	0.04		**0.39**	**0.49**	**0.28**	0.01
Mo	**0.20**	**0.49**	**0.32**	**0.28**	**0.30**	**0.55**	**0.22**	0.22		**0.57**	**0.56**	0.00
W	0.00	0.17	**0.26**	0.07	**0.26**	**0.40**	**0.27**	**0.36**	**0.76**		**0.36**	-0.003
Co	0.12	0.17	0.25	0.19	**0.32**	**0.43**	**0.29**	**0.30**	**0.54**	**0.77**		0.01
V	-0.10	**0.30**	**0.29**	0.17	**0.41**	**0.39**	**0.41**	**0.47**	**0.55**	**0.60**	**0.50**	
Ore zones 3 and 5; 500 samples; significance level – 0,13												

4 Conclusions

In conclusion, the ore concentrations of gold and silver in zones 2, 3, and 5 of the Okzhetpes ore field appear to be derived primarily from sedimentogenic sources of metals and sulfur. This sedimentary origin suggests that the mineralization processes in these zones are closely linked to the initial metal and sulfur content within the host rocks, influenced by sedimentary and diagenetic processes that concentrated these elements. As a result, the ore potential of such deposits is largely contingent on the extent of the metal-bearing sedimentary environment and the transformative geological processes that enable metal enrichment and accumulation.

The identification and assessment of these sedimentogenic metal systems are thus of significant practical value. Evaluating the scale and geochemical characteristics of the metal-rich sedimentary environments, along with understanding the alteration processes that convert these environments into viable ore bodies, are essential for effective resource exploration and development. This approach not only aids in defining the mineral potential of similar geological settings but also enhances the predictive capability for locating economically valuable ore zones within sedimentary formations.

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