International Journal of Geology, Earth & Environmental Sciences ISSN: 2277-2081
An Open Access, Online International Journal Available at http://www.cibtech.org/jgee.htm
2026 Vol. 16, pp. 57-62/Mustafaev
Research Article

TRACE ELEMENT GEOCHEMISTRY OF SPHALERITE AND GALENA FROM THE KULCHULAK PB-ZN DEPOSIT, ALMALYK ORE DISTRICT, UZBEKISTAN: IMPLICATIONS FOR ORE GENESIS AND EXPLORATION

***Mustafaev Bakhtishod Nurali ugli**
Almalyk State Technical Institute, Almalyk, Uzbekistan
**Author for Correspondence: bakhtishod@mail.ru*

ABSTRACT
The Kulchulak deposit is a stratiform Pb-Zn occurrence located in the Central tectonic block of the Almalyk ore district (Middle Tien Shan, Uzbekistan). The ore bodies are hosted in Famennian dolomites of the Kulota and Karatogota formations. In this paper, we present new data on the trace element composition of sphalerite and galena from the central section of the deposit, based on 43 mineralogical samples and 213 chemical analyses collected during the field campaigns of 2018–2021. Sphalerite shows moderate Fe contents (mean 4.6 wt%) and rather high Cd (mean 0.21 wt%), and contains detectable amounts of Se, Te and Bi. Galena, in turn, is the main carrier of Ag (up to 280 g/t) and also hosts traces of Au and Bi. These results, together with our earlier observations on the morphology and the structural setting of the ore bodies (Mustafaev, 2021; Mustafaev, Turapov, & Ziyomov, 2025), are most consistent with a polygenic and polychronous model of ore formation, in which an initial sedimentary pre-concentration was followed by a hydrothermal redistribution stage related to Hercynian magmatism. The Pb-Zn-Ag-Cd-Bi association established in this study can be used as a practical geochemical fingerprint for further exploration of similar carbonate-hosted Pb-Zn targets within the Almalyk ore district.

Keywords: *Sphalerite; Galena; Trace elements; Carbonate-hosted Pb-Zn deposit; Kulchulak; Almalyk ore district; Tien Shan; Uzbekistan*

INTRODUCTION
Carbonate-hosted Pb-Zn deposits remain one of the main sources of zinc and lead in the world (Leach *et al.,* 2010; Wilkinson, 2014). In Central Asia, and in Uzbekistan in particular, these deposits are an important part of the mineral resource base. The Almalyk ore district has been known since the early decades of the twentieth century, mostly because of its world-class porphyry Cu-Mo systems. The Pb-Zn deposits of the same area, however, were studied less actively in recent decades, even though they still contain considerable resources and play an important role for the economy of the region (Khamrabaev, 1969; Golovanov, 2001).
After the Korgashinkon mine has been almost fully worked out, the question of expanding the lead-zinc raw material base of the country has become really urgent. In this situation, deposits located on the flanks of the well-known mining fields, as well as small but well-studied stratiform occurrences, attract a renewed attention. The Kulchulak deposit, located in the south-eastern part of the Central tectonic block, is a typical representative of stratiform Pb-Zn mineralization hosted by Upper Devonian carbonate rocks. We have presented the geological structure of the Chatkal-Kurama mountains, where this deposit is located, in our earlier paper (Mustafaev, 2021).
The geological position, morphology of the ore bodies and ore-controlling factors of the Kulchulak deposit have been already discussed by us in a number of papers (Mustafaev, Ziyomov, Juraev, & Gapurov, 2024; Mustafaev, 2025; Mustafaev, Turapov, & Saidov, 2026; Mustafaev & Turapov, 2026). The morphogenesis of the ore bodies of polymetallic deposits of Central Asia, including Kulchulak, was reviewed in Mustafaev, Turapov, and Ziyomov (2025). However, the trace element composition of the

main sulfide minerals — sphalerite and galena — was not addressed in detail in those works. This is the main reason why we decided to carry out the present study.

Trace elements in sphalerite and galena are widely used today as sensitive indicators of the conditions of ore formation. The contents of Fe, Cd, Mn, Ga, Ge, In, Se and Te in sphalerite, as well as Ag, Au and Bi in galena, often provide robust information on the temperature, the source of the metals and the type of the deposit (Cook et al., 2009; Ye et al., 2011; Frenzel, Hirsch, & Gutzmer, 2016; George, Cook, Cristiana, & Wade, 2015). For the deposits of the Tien Shan belt, similar approaches have been applied successfully in several studies (Seltmann, Porter, & Pirajno, 2014; Yakubchuk, Cole, Seltmann, & Shatov, 2002), but for the Almalyk Pb-Zn occurrences such systematic data have remained scarce.

Finally, we suggest a set of geochemical criteria that can be used as a practical exploration vector for the search of similar Pb-Zn targets within the Almalyk ore district and beyond it.

2. Geological setting

2.1 Regional framework

The Almalyk ore district occupies the northern slope of the Kurama Range, in the Middle Tien Shan. According to the tectonic subdivision of Popov (1938), this area belongs to the Kurama structural-facies zone. Two superimposed tectono-magmatic cycles can be distinguished here. The Caledonian cycle ($\alpha S–D_1$) is represented mainly by amphibole gabbros, granodiorites, biotite granites and granodiorite-porphyries. The Hercynian cycle ($\varepsilon\delta C_2$ and younger) includes syenite-diorites of the Almalyk type, granodiorites of the Kurama type, and a variety of subvolcanic porphyry intrusions. The polymetallic mineralization of the district, including the Kulchulak deposit, is genetically related to the second cycle, as we have already discussed in detail in Mustafaev (2021).

The district is divided by a number of large faults into four tectonic blocks — Northern, Central, Southern and South-Eastern. Most of the polymetallic deposits, including Kulchulak, are concentrated in the Central block, where carbonate-volcanogenic sequences are best developed and structural conditions are most favourable for the localization of mineralization.

2.2 Stratigraphy and host rocks of the Kulchulak deposit

The geological structure of the Kulchulak deposit involves Middle and Upper Palaeozoic carbonate and volcanogenic-sedimentary formations. The oldest rocks exposed in the area are quartz porphyries of Lower Devonian age. Above them, an extended carbonate sequence is developed, which is subdivided into the Olmaliq, Karatogota and Kulota formations of late Frasnian–Famennian age, and the Kulchulak Formation of Tournaisian–Visean age. The whole sequence is unconformably overlain by the andesite-dacite porphyries of the Akcha Formation (C_2ak), which represent the volcanogenic component of the section.

The main ore-bearing horizon of the Kulchulak deposit is represented by the Famennian dolomites of the Kulota and Karatogota formations. The same stratigraphic position is observed for many other Pb-Zn occurrences within the Central block, which clearly indicates a strong lithological control on the mineralization. The role of the carbonate and volcanogenic-sedimentary deposits in the localization of the Kulchulak mineralization was specially considered in Mustafaev (2025).

2.3 Ore-controlling factors and morphology

Three main factors control the localization of Pb-Zn mineralization at the Kulchulak deposit. The lithological factor is expressed by the preferential occurrence of ore bodies within the dolomites and dolomitized limestones of the Famennian sequence. The structural factor reflects the localization of the ore in bedding-parallel zones, in zones of small folds, in brecciation zones, and in intersections of large faults. The magmatic factor is expressed in the close spatial and temporal association of mineralization with the andesite-dacite-rhyolite formation, especially along contacts between carbonate and volcanogenic rocks.

The morphology of the ore bodies in the Kulchulak deposit was studied in detail by us earlier (Mustafaev, Ziyomov, Juraev, & Gapurov, 2024; Mustafaev, Turapov, & Ziyomov, 2025). Five main morphological types of ore bodies were distinguished: stratiform, ribbon-shaped, lenticular, saddle-shaped and complex.

According to the classification of polymetallic deposits of Central Asia, the Kulchulak deposit belongs to the contact group, since most of its ore bodies are spatially associated with contacts between sedimentary carbonate and volcanogenic rocks. The patterns of distribution of the mineralization and the prognostic resources of the deposit have been recently summarized in Mustafaev, Turapov, and Saidov (2026).

MATERIALS AND METHODS

3.1 Sampling

The samples used in this study were collected during the field campaigns of 2018–2021, carried out within the framework of the research project of the Almalyk Branch of Tashkent State Technical University. The sampling was designed to cover all the main lithological units, the principal morphological types of the ore bodies, and the vertical extent of the mineralized zone in the central part of the deposit.

3.2 Analytical procedures

Polished thin sections and ore polished sections were studied using transmitted and reflected light microscopes, in order to characterize mineral assemblages, textures, and the relative timing of the mineral generations. Selected samples were further examined by scanning electron microscopy with energy-dispersive spectrometry (SEM-EDS), which allowed us to identify minor and accessory phases and to obtain semi-quantitative data on the major sulfide minerals.

The trace element suite, including Cd, Se, Te, Bi, Ag and Au, was determined additionally by inductively coupled plasma mass spectrometry. The analytical work was carried out in the certified laboratories of the Institute of Mineral Resources and the Central Geological Survey Laboratory of Uzbekistan. Internal and certified reference materials were used for the quality control. The reported uncertainties for the major elements are within ±5% (relative), and for the trace elements within ±10–15% (relative), depending on the concentration level.

RESULTS

4.1 Ore mineralogy

The mineral composition of the Kulchulak ores is dominated by four main ore minerals — pyrite, galena, sphalerite, and chalcopyrite. The estimates from the polished sections of the central part of the deposit indicate the following average modal proportions: about 38% of pyrite, 24% of galena, 22% of sphalerite, and 9% of chalcopyrite. The remaining 7% are represented by minor and accessory phases, including magnetite, hematite, fahlores (tetrahedrite-tennantite group), leucoxene, bornite, chalcocite, arsenopyrite and stibnite. The non-ore (gangue) mineralogy is composed mainly of quartz, calcite, dolomite, amphibole and wollastonite.

Table 1: Average trace element composition of sphalerite and galena from the central section of the Kulchulak deposit (n = 43 mineralogical, n = 213 chemical samples). Concentrations are given in wt% for the major elements and in g/t for the trace elements; b.d.l. = below the detection limit.

Element	**Unit**	**Sphalerite (mean)**	**Galena (mean)**	**Range**
Zn	wt%	**60.5**	—	58.2 – 63.1
Pb	wt%	—	**85.7**	82.0 – 86.6
S	wt%	32.1	13.2	—
Fe	wt%	**4.6**	0.05	2.8 – 7.2 (sph)
Cd	wt%	**0.21**	b.d.l.	0.12 – 0.34 (sph)
Ag	g/t	12	**180**	90 – 280 (gn)
Au	g/t	b.d.l.	0.6	0.2 – 1.4 (gn)
Bi	g/t	18	45	8 – 80
Se	g/t	32	28	12 – 65
Te	g/t	9	14	4 – 32

Texturally, sphalerite occurs as fine- to medium-grained aggregates intergrown with galena and pyrite. In a number of samples, sphalerite shows characteristic emulsion-like exsolutions of chalcopyrite, the so-called "chalcopyrite disease". Galena forms anhedral grains and granular masses, often partially replacing earlier sphalerite. Pyrite occurs both as early framboidal aggregates and as later euhedral crystals, which are typically associated with galena and sphalerite. This indicates more than one generation of pyrite, and supports the polychronous nature of the mineralization.

4.2 Trace element composition of sphalerite

Sphalerite from the central part of the Kulchulak deposit shows a relatively narrow compositional range. The Fe content varies from 2.8 to 7.2 wt%, with a mean value of approximately 4.6 wt% (Table 1). Such a level of Fe is intermediate between the very low values, which are typical of the classical low-temperature MVT-style sphalerites, and the higher values, which are usually reported for the high-temperature skarn or volcanogenic systems. In our opinion, this is most consistent with a formation under medium-temperature hydrothermal conditions in a carbonate-hosted environment, similar to the conditions described by Cook et al. (2009) and Frenzel et al. (2016) for many comparable deposits worldwide.

The Cd content of sphalerite is consistently elevated, with the mean value of 0.21 wt%, and the maximum reaching 0.34 wt%. The corresponding Cd/Zn ratio (about 3.5×10^{-3}) is also typical of medium-temperature hydrothermal sphalerites. Selenium and tellurium are systematically detected at the level of tens of g/t, while bismuth is present at lower but still consistent concentrations. We consider that the simultaneous presence of Se, Te and Bi in sphalerite is an important indicator of a magmatic component in the source of the ore-forming fluids, since these elements are usually depleted in purely sedimentary brines (Ye et al., 2011; Belissont, Boiron, Luais, & Cathelineau, 2014).

4.3 Trace element composition of galena

Galena is the principal carrier of silver in the Kulchulak ores. The mean Ag concentration is about 180 g/t, and individual values reach up to 280 g/t. Detectable concentrations of gold (mean 0.6 g/t) and elevated bismuth (mean 45 g/t) are also characteristic. The Ag-Au-Bi association in galena is generally considered as an indicator of medium-temperature hydrothermal origin (George et al., 2015). In our case, this association supports the interpretation that the ore-forming fluids were not represented by pure basinal brines, but received a noticeable input from magmatic-derived components.

A clear vertical zonality has been observed within the central section of the deposit. The contents of Cu, Zn and Pb increase distinctly with depth in the interval from 0 to 400 m, and then decrease again towards 500 m. The maximum Cu content of about 4500 g/t was registered at the depth interval of 300–400 m, where Zn reaches 3200 g/t and Pb 1400 g/t. Such a pattern is typical of a system in which the focusing of the ore-forming fluids was strongest at intermediate depths, and was controlled by the intersections of bedding-parallel zones with steeply dipping faults — exactly as predicted by the structural model that we have proposed earlier (Mustafaev, Ziyomov, Juraev, & Gapurov, 2024).

DISCUSSION

5.1 Conditions of ore formation

The combined geochemical signature of sphalerite and galena from the Kulchulak deposit — moderately Fe-rich sphalerite with elevated Cd content, and Ag-Au-Bi-bearing galena — is most consistent with formation from medium-temperature hydrothermal fluids of mixed magmatic-meteoric origin. The detectable presence of Se, Te and Bi strongly suggests that a magmatic component contributed to the metal budget of the system. At the same time, the carbonate host rocks, the presence of bedding-parallel zones, and the occurrence of lenticular ore bodies show that the migration and the deposition of these fluids were strongly controlled by the sedimentary stratigraphy of the host sequence.

These conclusions are consistent with the polygenic and polychronous model of ore formation that has been proposed for the Almalyk district in our previous works (Mustafaev, 2021; Mustafaev, 2025; Mustafaev & Turapov, 2026). According to this model, an initial syngenetic stage of metal pre-concentration in the carbonate sediments of the Famennian basin was followed, after the emplacement of the Hercynian intrusions, by an epigenetic stage of hydrothermal redistribution and concentration of metals into structurally favourable traps. The trace element data presented above provide an independent geochemical confirmation for the magmatic-hydrothermal component of this two-stage evolution. It should be noted that such a hybrid model is also in agreement with the regional metallogenic framework of the Tien Shan belt, as it has been described by Seltmann et al. (2014) and Yakubchuk et al. (2002).

5.2 Comparison with other Pb-Zn systems

When the Kulchulak deposit is compared with other carbonate-hosted Pb-Zn systems, an intermediate position becomes apparent. On the one hand, classical Mississippi Valley Type (MVT) deposits are typically characterized by low Fe contents, low Ag values and very low Se-Te-Bi values in their sulfides (Leach et al., 2010; Wilkinson, 2014). On the other hand, the Irish-type and skarn-related carbonate-hosted systems usually contain sulfides which are richer in Fe, Ag and Bi. The trace element signature of Kulchulak — Fe-rich sphalerite combined with Ag- and Bi-bearing galena — is most similar to that reported for several deposits of the South Tien Shan and the Rudny Altai region, where a clear magmatic-hydrothermal contribution has been previously demonstrated (Yakubchuk et al., 2002; Seltmann et al., 2014).

We therefore consider that the Kulchulak deposit cannot be classified as a pure MVT-style occurrence. Rather, it should be regarded as a hybrid carbonate-hosted system, in which both the sedimentary architecture of the host basin and the subsequent magmatic-hydrothermal activity played essential roles. This conclusion is in line with our recent observations on the metallogenic relationships between the Pb-Zn and Cu-porphyry mineralization in the Almalyk district (Mustafaev & Turapov, 2026), which suggest that both types of mineralization are products of one and the same Hercynian metallogenic event, but at different levels of the magmatic-hydrothermal system.

5.3 Implications for further exploration

From the practical point of view, the trace element data presented in this study can be directly translated into a set of useful exploration criteria for the Almalyk district and similar settings. Three points should be especially emphasized.

First, the consistent occurrence of elevated Cd in sphalerite, together with the Ag-Bi association in galena, defines a recognizable Pb-Zn-Ag-Cd-Bi geochemical fingerprint. This fingerprint can be used in regional geochemical surveys in order to discriminate Kulchulak-type mineralization from other ore types, such as the porphyry Cu-Mo systems of the same district.

Second, the strong vertical zonality, observed in the central section, with the metal concentrations peaking at 300–400 m depth, suggests that the exploration drilling in similar lithological-structural settings should target depths of several hundred metres, rather than be concentrated only on the near-surface occurrences.

Third, the close spatial association of the mineralization with the contacts between the Famennian carbonate rocks and the overlying volcanogenic units defines a clear lithological-structural target for follow-up exploration in the flank zones of the known deposits. On the basis of these criteria, three prospective sub-areas have already been delineated within and adjacent to the Kulchulak deposit (Mustafaev, Turapov, & Saidov, 2026), and their further evaluation can be recommended as a priority for the next stage of exploration in the Central block of the Almalyk district.

6. Conclusions

On the basis of the trace element study of sphalerite and galena from the Kulchulak Pb-Zn deposit, the following main conclusions can be drawn.

1. Sphalerite from the central part of the deposit is characterized by moderate Fe contents (mean 4.6 wt%), elevated Cd (mean 0.21 wt%) and detectable concentrations of Se, Te and Bi. This composition indicates a formation from medium-temperature hydrothermal fluids with a clear magmatic contribution.
2. Galena hosts the bulk of the silver (mean 180 g/t, up to 280 g/t), together with detectable Au and Bi. The Pb-Ag-Au-Bi association is both economically significant and genetically diagnostic.

3. The combined geochemical signature, taken together with the structural and morphological data published earlier (Mustafaev, 2021; Mustafaev et al., 2024; Mustafaev, Turapov, & Ziyomov, 2025; Mustafaev, 2025), supports the polygenic and polychronous model of ore formation. Both syngenetic concentration of metals in the host carbonates and an epigenetic redistribution by magmatic-hydrothermal fluids related to the Hercynian cycle have to be taken into account.
4. The Pb-Zn-Ag-Cd-Bi geochemical fingerprint, together with the observed vertical zonality, can be used as a practical exploration vector for the search of similar carbonate-hosted Pb-Zn targets within the Central block of the Almalyk district, as well as in comparable settings of the Middle Tien Shan.

Future studies should ideally include in situ trace element analyses of individual sulfide grains by laser ablation ICP-MS, stable isotope studies (S, O, Pb) for a more detailed reconstruction of the sources of the ore-forming fluids, and the construction of a three-dimensional structural-geochemical model of the deposit, which would allow to optimize the planning of further exploration drilling.

REFERENCES

Belissont, R., Boiron, M.-C., Luais, B., & Cathelineau, M. (2014). LA-ICP-MS analyses of minor and trace elements and bulk Ge isotopes in zoned Ge-rich sphalerites. *Geochimica et Cosmochimica Acta,* **126**, 518–540.

Cook, N. J., Ciobanu, C. L., Pring, A., Skinner, W., Shimizu, M., Danyushevsky, L., Saini-Eidukat, B., & Melcher, F. (2009). Trace and minor elements in sphalerite: A LA-ICPMS study. *Geochimica et Cosmochimica Acta,* **73**(16), 4761–4791.

Frenzel, M., Hirsch, T., & Gutzmer, J. (2016). Gallium, germanium, indium, and other trace and minor elements in sphalerite as a function of deposit type — A meta-analysis. *Ore Geology Reviews,* **76**, 52–78.

George, L., Cook, N. J., Cristiana, C. L., & Wade, B. P. (2015). Trace and minor elements in galena: A reconnaissance LA-ICP-MS study. *American Mineralogist,* **100**(2-3), 548–569.

Golovanov, I. M. (2001). Ore deposits of Uzbekistan. Tashkent: Institute of Mineral Resources.

Khamrabaev, I. K. (1969). Magmatism and post-magmatic processes in the Western Tien Shan. Tashkent: Fan.

Leach, D. L., Bradley, D. C., Huston, D., Pisarevsky, S. A., Taylor, R. D., & Gardoll, S. J. (2010). Sediment-hosted lead-zinc deposits in Earth history. *Economic Geology,* **105**(3), 593–625.

Mustafaev, B. N. (2021). Geological structure of the Chatkal-Kurama Mountains. *Oriental Renaissance: Innovative, Educational, Natural and Social Sciences*, **1**(5), 646–654.

Mustafaev, B. N., Ziyomov, B. Z., Juraev, F. X., & Gapurov, M. F. (2024). Form of ores in polymetallic deposits of Uzbekistan. *Scientific Journal of the National University of Uzbekistan named after Mirzo Ulugbek*, (3/2/1), 233–235.

Mustafaev, B. N., Turapov, M. K., & Ziyomov, B. Z. (2025). On the study of morphogenesis of ore bodies of polymetallic deposits of Central Asia. *European Journal of Interdisciplinary Research and Development*, **36**, 188–194.

Mustafaev B.N., (2025). Connection of Paleozoic carbonate and volcanogenic-sedimentary deposits with mineralization at the Kulchulak polymetallic deposit. *European Journal of Interdisciplinary Research and Development,* **46**, 178–183.

Turapov M.K., Mustafaev B.N., & Saidov X.L. (2026). Qulcho‘loq konida polimetall ma'danlashuvi joylashish qonuniyatlari va prognoz resurslari. *Sanoatda raqamli texnologiyalar,* **4**(1), 31–35.

Turapov M.K., Mustafaev B.N. (2026). Olmaliq ma'danli hududida qo‘rg‘oshin-rux va mis porfirning metallogen munosabatlari. *Sanoatda raqamli texnologiyalar,* **4**(1), 25–30.

Popov, V. I. (1938). Tectonic zoning of Western Uzbekistan. Tashkent: Uzbek Branch of the USSR Academy of Sciences.

Seltmann, R., Porter, T. M., & Pirajno, F. (2014). Geodynamics and metallogeny of the central Eurasian porphyry and related epithermal mineral systems: A review. *Journal of Asian Earth Sciences,* **79**, 810–841.