Код МРНТИ 38.35.21

**M.A. Mizernaya, *B.B. Agalieva, Zh.A. Shayakhmetova, Y.T. Yeskaliyev**
*D. Serikbayev East Kazakhstan Technical University (Ust-Kamenogorsk, Kazakhstan)*

# FEATURES OF THE MICROELEMENT COMPOSITION OF ORE OF THE ARTEMYEVSKOYE DEPOSIT (RUDNY ALTAI)

**Abstract.** The mineralogical composition of ores from the Artemyevskoye deposit, located in the Irtysh ore district of the Rudny Altai polymetallic belt, has been investigated. The ores exhibit complex mineralogical zoning and are classified into barite-polymetallic, polymetallic, copper-zinc, and copper types. Both the primary ores and their beneficiation products contain elevated concentrations of a wide range of trace elements, which in many cases exceed the clarke values for volcanogenic-sedimentary rocks by an order of magnitude or more. Against the background of progressive depletion of polymetallic ore reserves in the Rudny Altai, the processing and recycling of mining and beneficiation waste are considered a potentially sustainable source not only of major metals but also of strategically important and commercially valuable by-products (***Bi***, ***Cd***, ***Ga***, ***Sb***, ***In*** and others).
***Key words****: Rudny Altai belt, polymetals, mineral composition, sulfide ores, rare elements, waste recycling, sustainable mining.*

**Артемьев кен орнының кендерінің микроэлементтік құрамының ерекшеліктері (Кенді Алтай)**

**Андатпа.** Артемьев кенорнының минералдық құрамы зерттелді. Кенорны кенді Алтай полиметалл белдеуінің Прииртыш кен ауданы аумағында орналасқан. Кендер күрделі минералдық аймақталуымен ерекшеленеді және барит-полиметаллды, полиметаллды, мыс-мырышты және мыс типтеріне бөлінеді. Түпкі кендер де, оларды байыту өнімдері де микроэлементтердің кең спектрінің жоғары концентрацияларын қамтиды, олар көптеген жағдайларда жанартаутектітерригенді жыныстарға тән кларк мәндерінен бір немесе бірнеше ретті жоғары болады. Кенді Алтайдағы полиметалл кендерінің қорының біртіндеп сарқылу жағдайында өндіру және байыту кезіндегі техногендік қалдықтарды қайта өңдеуге тарту негізгі металдардың ғана емес, сонымен қатар стратегиялық маңызды және коммерциялық тұрғыдан құнды қоспа компоненттердің (***Bi***, ***Cd***, ***Ga***, ***Sb***, ***In*** және т. б.) тұрақты көзі ретінде қарастырылады.
***Түйінді сөздер:*** *Кенді Алтай белдемі, полиметалдар, минералдық құрамы, сульфидті кендер, сирек элементтер, қалдықтарды қайта өңдеу, тұрақты таукен өндірісі.*

**Особенности микроэлементного состава руд Артемьевского месторождения (Рудный Алтай)**

**Аннотация.** Изучен минералогический состав руд месторождения Артемьевское, расположенного в Прииртышском рудном районе Рудно-Алтайского полиметаллического пояса. Руды характеризуются сложной минералогической зональностью и подразделяются на барит-полиметаллические, полиметаллические, медно-цинковые и медные типы. Как коренные руды, так и продукты их обогащения содержат повышенные концентрации широкого спектра микроэлементов, которые во многих случаях превышают кларковые значения для вулканогенно-осадочных пород на порядок и более. На фоне прогрессирующего истощения запасов полиметаллических руд Рудного Алтая вовлечение в переработку техногенных продуктов добычи и обогащения рассматривается как потенциально устойчивый источник не только основных металлов, но и стратегически важных и коммерчески значимых попутных компонентов (***Bi***, ***Cd***, ***Ga***, ***Sb***, ***In*** и др.).
***Ключевые слова:*** *Рудно-Алтайский пояс, полиметаллы, минеральный состав, сульфидные руды, редкие элементы, переработка отходов, устойчивая добыча полезных ископаемых.*

## Introduction

In recent years, due to rising global prices for non-ferrous metals, the problem of replenishing the mineral resource base for strategically important rare and non-ferrous metals has become particularly acute in Kazakhstan. The main constraints to the development of the mining industry in the republic include limited geological exploration and a declining supply of raw materials, largely due to the lack of comprehensive extraction of useful ore components.

One illustrative example of the complex composition of ores is the Artemyevskoye polymetallic deposit, located in the East Kazakhstan region. It is one of the major deposits in the Rudny Altai region and is distinguished by significant volumes of both mined and accumulated man-made formations, which can be considered a promising source of non-ferrous and rare metals.

The purpose of this article is to clarify the mineral and elemental composition of various commercial ore types at the Artemyevskoye polymetallic deposit, identifying associated rare metal mineralization.

The main objectives are to study the mineral and trace element composition of primary ores and man-made mineral formations (dumps and beneficiation tailings); using modern, high-precision laboratory research methods (ICP-MS, scanning electron microscopy), to clarify the composition and contents of commercially attractive by-products in ores and beneficiation products.

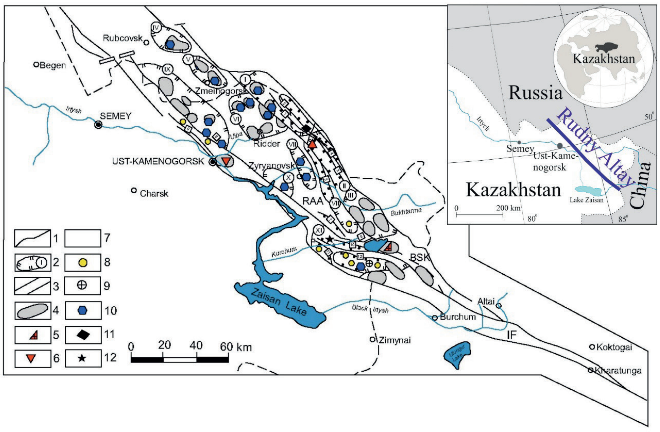
The study examines the geological structure and mineral composition of the Artemyevsky deposit, assesses the rare metal resources in its ores, and examines the potential of the beneficiation plant's tailings ponds as a source of secondary metals.

## Material and methods

The research methodology was based on a comprehensive analysis of geological data from prospecting and exploration work conducted at various times. Samples were collected from various ore types at the Artemyevskoye deposit (50 specimens). The mineral and elemental composition of the ores was studied using modern analytical methods: inductively coupled plasma mass spectrometry (ICP-MS) to determine the weight content of trace elements, and scanning electron microscopy with energy-dispersive analysis to study the mineral composition [1].

***Geological structure of the Artemyevsky deposit.*** The Artemyevskoye deposit is located 9 km from the town of Shemonaikha in the East Kazakhstan region. It was discovered in 1984 and is currently developed by Kazakhmys JSC. The deposit is located in the Priirtyshsky ore district of the Kazakh part of Rudny Altai (Fig. 1) and is part of the Artemyevsko-Kamyshinskaya ore zone. In plan view, the ore zone is traced between the Kamyshinsky and Artemyevsky blocks; the Kamyshinskoye deposit (discovered in 1958) was developed earlier, while the Artemyevskoye deposit was explored between 1985 and 1993 and commissioned in 2005 (according to other sources, pilot production since 1994, and full-scale production since 2005) [2, 3].

The Kamyshin-Artemyevsk ore zone extends for approximately 4 km, is approximately 600 m wide, and is up to 200 m thick. Its structures are nearly flat, dipping northeast-




*1 – boundaries of the Rudny-Altai belt; 2 – boundaries of ore regions (I, II, III – Bukhtarma, IV – Rubtsovsky, V- Zmeinogorsk, VI – Leninogorsk, VII – Zyryanovsky, VIII, IX – Priirtyshsky); 3 – Irtysh shear zone; 4 – ore regions; 8-12 – deposits: 8 – copper; 9 – copper-zinc; 10 – pyrite-polymetallic; 11 – lead-zinc; 12 – zinc-lead*

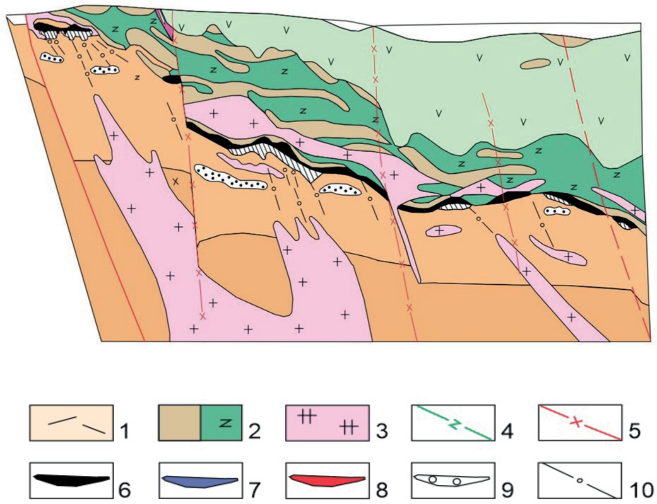
**Figure 1. Layout of the Rudnoaltai pyrite-polymetallic belt.**
**Сурет 1. Кендіалтай колчедан-полиметалл белдеуін орналастыру схемасы.**
**Рис. 1. Схема размещения Рудноалтайского колчеданно-полиметаллического пояса.**

ward. The ore depth increases from southwest to northeast: while in the Kamyshinsky area (southwestern flank of the zone), ores were exposed at the surface (depths from 0 to 50 m), in the area of the Artemyevskoye deposit itself (northeastern flank), mineralization descends to a depth of ~900 m (Fig. 2). The main ore deposits of the Artemyevsky deposit are located in the depth range of 600–1600 m (Main deposit) and 800–1000 m (Western deposit), while smaller lens-shaped bodies are located at average depths of approximately 640–950 m. The thickness of individual ore bodies varies from a few meters to tens of meters (usually 6–17 m, maximum up to 40 m).

Ore mineralization is confined to volcanogenic-sedimentary rocks of the middle devonian ($D_2$). The main ore bodies are concentrated within the contact of siltstones and basalts of the Gerikhovskaya Formation (lower frasnian $D_2f_1$ substage) with the overlying tuffs and lava breccias of the rhyolites of the Talovskaya Formation (middle Devonian $D_2tl$). The ore field is complicated by intrusions of dacitic and diabase dikes associated with Late Devonian magmatism; however, the main contrasting granitoid intrusions are absent [4].

The formation of ore bodies was accompanied by intense hydrothermal-metasomatic alteration of the host rocks. At the base of the ore deposits, the rock section is heavily permeated with vein-disseminated sulfide mineralization: the host siltstones are observed to grow into zones of microquartzite, sericitolite, chloritolite, and quartz-sericite-chlorite metasomatites. Roof (hanging wall) rocks near the contact with the ore body are silicified and sericitized, reflecting the influence of post-ore hydrothermal solutions [5].

A fairly consistent vertical zonation is observed in the spatial distribution of the identified natural varieties of all the main ore bodies of the deposit. In the generalized ore intersection, the natural varieties are separated in the following sequence (from top to bottom): silver-polymetallic (lean, low-sulfide); barite-polymetallic (rich and ultra-rich); polymetallic; copper-zinc; copper.




*1 – lava breccias of porphyry of the Talovskaya suite; 2 – siltstones -a and diabases b of the Gerikhovskaya suite; 3 – porphyry; 4 – porphyrites; 5 – plagiogranite-porphyry; 6 – copper-pyrite ores; 7 – copper-zinc ores; 8 – polymetallic ores; 9 – disseminated polymetallic mineralization; 10 – veinlet-disseminated copper mineralization*

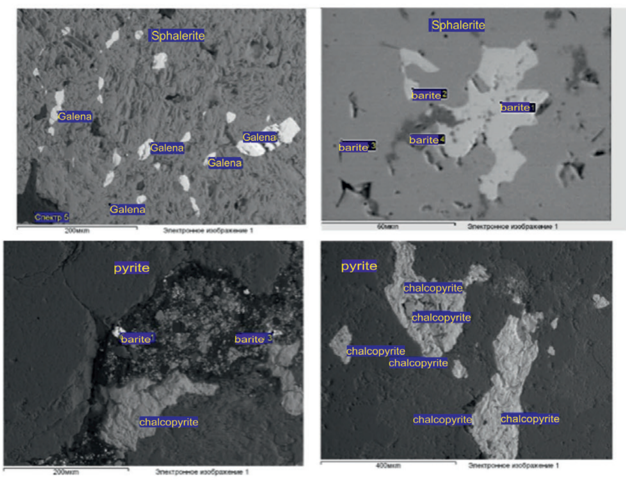
**Figure 2. Longitudinal geological section of the Artemyevsky deposit.**
**Сурет 2. Артемьев кен орнының бойлық геологиялық бөлімі.**
**Рис. 2. Продольный геологический разрез Артемьевского месторождения.**

*Features of the mineral composition of the ores of the Artemyevsky deposit***.** Main ore minerals. The ores of the Artemyevsky deposit are characterized by a complex polymineral composition. The total number of minerals exceeds 60, including 44 ore minerals. The main ore minerals are sphalerite (***ZnS***), galena (***PbS***), chalcopyrite (***CuFeS₂***), and pyrite (***FeS₂***). Minor ore minerals include fahlore, pyrrhotite, marcasite, bornite, chalcocite, arsenopyrite, magnetite, and minerals of gold, silver, germanium, bismuth, and others.

«Fahlores» – a finely crystalline mixture of complex sulfosalts of silver, copper, antimony, and arsenic (phases such as freibergite, tetrahedrite, and tennantine) – play a significant role. The aforementioned sulfosalts (tetrahedrite-freibergite), as well as arsenopyrite (***FeAsS***), marcasite (***FeS2***, a parametric modification of pyrite), and other minerals are present as minor minerals. Rare and precious metals are noted among the rare minerals in the ores: native gold, electrum (***Au-Ag*** alloy), native silver and silver sulfides (acanthite $Ag_2S$, stephanite $Ag_5SbS_4$, polybasite $(Ag,Cu)_{16}Sb_2S_{11}$, etc.), as well as sulfosalts of bismuth (bismuthinite ***Bi2S3***), lead, and antimony (bournonite $PbSbS_3$, geocronite $Pb_{14}(Sb,As)_6S$, aikinite $PbCuBiS_3$, cosalite $Pb_2Bi_2S_5$, etc.). Thus, in addition to the main sulfides, the ores contain a wide range of rare metal minerals and noble elements in the form of finely dispersed inclusions [6, 7, 8].

The main rock-forming (non-metallic) minerals in the ore are quartz, chalcedony, sericite, chlorite, calcite, barite, and other minerals typical of hydrothermally altered effusive rocks. The presence of significant amounts of barite ($BaSO_4$) in the upper parts of the ore zone correlates with elevated barium concentrations in the ores and classifies the upper ores as belonging to the barite-polymetallic subtype of pyrite ores.

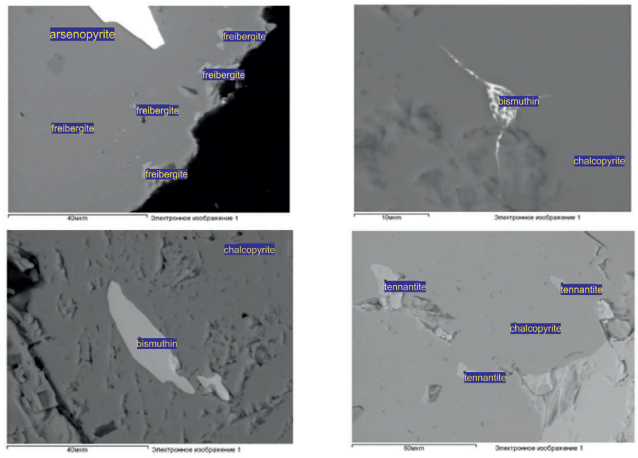
*Minerals of the main and noble metals.* The ores of the Artemyevsky deposit are classified as high-grade complex sulfide ores. The average grade of the main metals in the balance reserves is quite high: copper ~2.2%, lead ~2.2%, zinc ~7.6% (Fig. 3). In addition, the ores contain precious metals: gold ~0.17 g/t and silver ~13 g/t on average. According to the technological data of the processing plant, the gold content in the original ore can be about 0.6 g/t, and silver-up to 50–60 g/t (in the enriched mass, which depends on sampling and enrichment of high-grade areas). Thus, the ore composition contains industrial concentrations of ***Au*** and ***Ag***, which are extracted as a by-product during flotation enrichment (into copper and lead concentrate, or gravity concentrates are concentrated) [9, 10].




*a – 1 is the fluid dispersion of galena in sphalerite 3; b – barite crystals in sphalerite; c – 1, 3, 4 – galena, 2 – chalcopyrite in a large grain of pyrite; d – 1, 2, 3 chalcopyrite in pyrite*

**Figure 3. The ratio of the main ore minerals.**
**Сурет 3. Негізгі кен минералдарының қатынасы.**
**Рис. 3. Соотношение основных рудных минералов.**

*Trace and rare elements.* Along with the main sulfide minerals, gold and silver, the ores of the Artemyevsky deposit contain a whole complex of associated elements or rare metals. These include: cadmium (***Cd***), selenium (***Se***), indium (***In***), bismuth (***Bi***), antimony (***Sb***), mercury (***Hg***), arsenic (***As***), etc. The average contents of some of these elements in the ores of the Artemyevsky deposit, according to the State Reserves Committee, are: ***Cd*** from 80.0 to 480.0 g/t; ***Se*** from 40 to 70 g/t; ***Bi*** up to 80 g/t; ***Sb*** up to 470.0 g/t; ***As*** – 830.0 g/t; ***In*** up to 1.0 g/t; ***Se*** up to 45.4 g/t; ***Te*** up to 10.0 g/t; ***Tl*** 33.0 g/t; ***Ga*** – 15.4 g/t (Fig. 4).




*a – large grain of arsenopyrite, gray-fahlore (freibergite $Cu_{12}As_4S_{13}(Ag)$; b – bismuthinite with increased selenium content in chalcopyrite; c – fahlore in chalcopyrite; d – 3 – fahlore (tennantite $Cu_3AsS$) in a sphalerite grain*

**Figure 4. Microelement composition of ores of the Artemyovskoye deposit.**
**Сурет 4. Артемьев кен орны кендерінің микроэлементтік құрамы.**
**Рис. 4. Микроэлементный состав руд Артемьевского месторождения.**

The figure below (Fig. 5) presents the average concentrations of trace and minor elements (***Pb-Ni***, log scale) in ***Cu***-pyrite, pyrite, ***Cu***-pyrite-polymetallic, polymetallic, and barite-polymetallic ores of the Artemyevskoye deposit, based on ICP-MS analysis performed at the VERITAS laboratory of D. Serikbayev East Kazakhstan Technical University. The dashed black line indicates Clarke values for comparison [11].

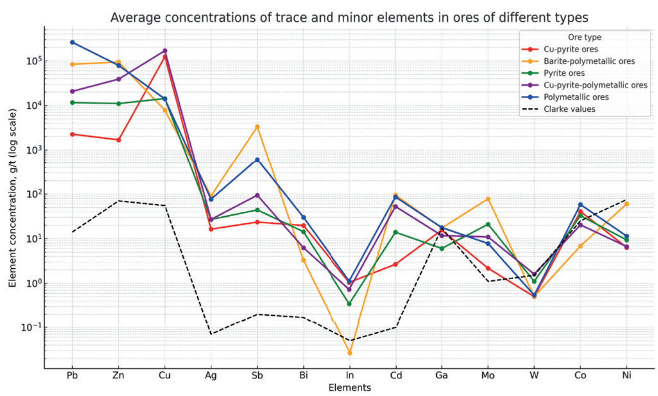



**Figure 5. Average concentrations of trace and minor elements in the different types of ores of Artemyevsky deposit.**
**Сурет 5. Артемьев кен орнының әр түрлі кендеріндегі сирек және қосымша элементтердің орташа концентрациясы.**
**Рис. 5. Средние концентрации редких и второстепенных элементов в различных типах руд Артемьевского месторождения.**

*Man-made mineral formations of ores of the Artemyevsky deposits.* Modern technologies for the extraction and processing of mineral raw materials ensure, on average, the utilization of only about 3% of the rock mass extracted from the subsoil; the remainder ends up in waste heaps and tailings dams. Up to 50% of non-ferrous metals are lost during the enrichment of complex ores, and the production of 1 ton of finished non-ferrous metal is accompanied by the formation of 1,000–3,000 tons of host and overburden rock and up to 100 tons of enrichment tailings.

Thus, with mineral resources becoming depleted, rational subsoil use and the inclusion of man-made formations in processing are becoming increasingly important. Ores from the Artemyevsky and neighboring deposits are processed at the Nikolayevskaya processing plant. Tailings from the Artemyevsky and other deposits primarily consist of gangue (quartz, sericite, chlorite, feldspar material) and pyrite remaining after the extraction of copper, lead, and zinc.

Metals in the tailings are present in trace amounts: zinc, copper, and lead together typically do not exceed fractions of a percent (e.g., ***Zn*** ~0.3–0.5%, ***Cu*** ~0.1–0.2%, ***Pb*** ~0.1% in final tailings), depending on the degree of extraction. When processing high-grade ores, some of the valuable component is always lost with tailings: for example, flotation recovery of zinc and lead is ~85–90%, copper ~70–80%, and gold ~60–70%, with the remainder ending up in tailings. Thus, significant metal resources accumulate in tailings dams. Estimates indicate that waste tailings may contain hundreds of thousands of tons of pyrite sulfur, tens of thousands of tons of zinc and copper, thousands of tons of lead, significant amounts of barium (as barite), as well as gold and silver distributed between the pyrite and silicate mass [12].

Furthermore, man-made tailings concentrate rare metals: the aforementioned indium, selenium, bismuth, and cadmium are almost entirely lost in tailings, as they are not specifically extracted. For example, with an average indium grade of ~1 g/t in ore, approximately 1 ton of indium accumulates in the annually generated tailings (volume > 1 million tons); Similarly, cadmium (approximately 50–80 g/t in ore) accumulates in tailings in tens of tons annually. A significant portion of selenium and tellurium associates with pyrite and also remains in the tailings.

From the analysis of this graph, it can be concluded that the tailings of the Nikolaev processing plant are an additional source of mineral resources for the additional extraction of non-ferrous, precious and rare metals.

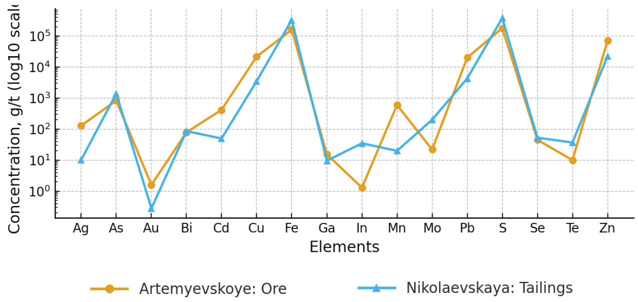



**Figure 6. The contents of the main elements in ores and tailings of the Artemyevskoye deposit.**
**Сурет 6. Артемьевское кен орнының кендері мен қалдықтарындағы негізгі элементтердің құрамы.**
**Рис. 6. Содержания основных элементов в рудах и хвостах месторождения Артемьевское.**

## Conclusion

According to the research results, it was established that the Artemyevskoye deposit, in addition to the main components (copper, zinc, lead), its ores and processed products contain a number of rare and trace elements. Significant volumes of already accumulated man-made waste dumps and enrichment tailings can be considered as secondary sources of valuable metals. Based on the obtained data, it is possible to recommend: (1) when processing the ores of the Artemyevskoye deposit, paying more attention to monitoring the distribution of indium, selenium, bismuth, etc. in the products, with the possibility of their selective concentration; (2) conducting pilot tests to extract ***Au*** and ***Ag*** from old tailings (for example, by heap leaching or gravity) – given that a significant portion of the gold remains in the tailings, this may be economically justified; (3) monitor the condition of the tailings storage facility and the quality of filtration waters, since the high content of sulphides (pyrite) in the tailings can lead to acid drainage and migration of elements such as ***As***, ***Cd***, ***Se*** – this requires environmental measures in parallel with the extraction of valuable components.

## Acknowledgments

***This research was carried out with the financial support of the Ministry of Science and Higher Education of the Republic of Kazakhstan under the scientific project BR24992854 «Development and implementation of competitive science-based technologies to ensure sustainable development of mining and metallurgy industry East Kazakhstan region».***

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**Information about the authors:**
***Mizernaya M.A.,*** Candidate of Geological and Mineralogical Sciences, Associate Professor at the School of Earth Sciences, D. Serikbayev East Kazakhstan Technical University (Ust-Kamenogorsk, Kazakhstan), *mizernaya58@bk.ru;* https://orcid.org/0000-0001-8618-7352
***Agaliyeva B.B.,*** Ph.D, Research Scientist, Senior Lecturer at the School of Earth Sciences, D. Serikbayev East Kazakhstan Technical University (Ust-Kamenogorsk, Kazakhstan), *agalieva_00@mail.ru;* https://orcid.org/0000-0002-5682-8451
***Shayakhmetova Zh.A.,*** Senior Lecturer at the School of Earth Sciences, D. Serikbayev East Kazakhstan Technical University (Ust-Kamenogorsk, Kazakhstan), *szhyldyz_1808@mail.ru;* https://orcid.org/0009-0009-8832-378X
***Yeskaliyev Y.T.,*** Postdoctoral Researcher, School of Earth Sciences, D. Serikbayev East Kazakhstan Technical University (Ust-Kamenogorsk, Kazakhstan), *yertayyeskaliyev@gmail.com;* https://orcid.org/0000-0003-0899-601X

**Авторлар туралы мәліметтер:**
***Мизерная М.А.,*** г-м.ғ.к, Жер туралы ғылымдар мектебінің қауымдастырылған профессоры, Д. Серікбаев атындағы Шығыс Қазақстан техникалық университеті (Өскемен қ., Қазақстан)
***Агалиева Б.Б.,*** Ph.D докторы, ІҒҚ, Жер туралы ғылымдар мектебінің аға оқытушысы, Д. Серікбаев атындағы Шығыс Қазақстан техникалық университеті (Өскемен қ., Қазақстан)
***Шаяхметова Ж.А.,*** докторант, жер туралы ғылымдар мектебінің аға оқытушысы, Д. Серікбаев атындағы Шығыс Қазақстан техникалық университеті (Өскемен қ., Қазақстан)
***Ескалиев Е.Т.,*** постокторант, Жер туралы ғылымдар мектебі, Д. Серікбаев атындағы Шығыс Қазақстан техникалық университеті (Өскемен қ., Қазақстан)

**Сведения об авторах:**
***Мизерная М.А.,*** к.г-м.н., ассоциированный профессор школы наук о Земле, Восточно-Казахстанский технический университет им. Д. Серикбаева (г. Усть-Каменогорск, Казахстан)
***Агалиева Б.Б.,*** доктор Ph.D, ВНС, ст. преподаватель школы наук о Земле, Восточно-Казахстанский технический университет им. Д. Серикбаева (г. Усть-Каменогорск, Казахстан)
***Шаяхметова Ж.А.,*** докторант, ст. преподаватель школы наук о Земле, Восточно-Казахстанский технический университет им. Д. Серикбаева (г. Усть-Каменогорск, Казахстан)
***Ескалиев Е.Т.,*** постдокторант школы наук о Земле, Восточно-Казахстанский технический университет им. Д. Серикбаева (г. Усть-Каменогорск, Казахстан)