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Radioactivity as a prospecting indicator of rare earth, gold and polymetal deposits in eastern Kazakhstan and an indicator of increased radioecological hazard during their development

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ABSTRACT
This study evaluates the role of natural radioactivity as an exploration indicator for rare-metal, gold, and polymetallic mineralization in Eastern Kazakhstan, as well as its significance as a factor of radioecological hazard. The analysis is based on the results of regional radiohydrolithochemical surveys conducted at a scale of 1:1,000,000, including bottom sediment sampling within microbasins. The study focuses on key natural radionuclides (U-238, Ra-226, Th-232, Ra-228, K-40) and their spatial distribution. Factor analysis was applied to identify anomalous geochemical associations and to assess their relationship with metallogenic structures. As a result, 80 potentially radioecologically hazardous zones were identified across Kazakhstan, including 5 zones within Eastern Kazakhstan. Within the study area, 12 anomalous sites were distinguished, characterized by 3–5 factors with cumulative explained variance ranging from 62.8% to 83.6%. The identified anomalies show spatial correspondence with major metallogenic zones, particularly the Rudny Altai and Kalba-Narym regions, which are associated with polymetallic and rare-metal mineralization. The results demonstrate that natural radioactivity can serve both as an effective exploration indicator and as an important factor of environmental risk. The study highlights the potential of integrating radioactivity parameters into exploration criteria and emphasizes the need to consider radiation safety in geological exploration and mining activities.

Keywords: radioactivity, prospecting indicator, gamma spectrometry, uranium, thorium, ore deposits.

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Introduction

Uranium and thorium are often genetically unrelated to many ore-forming elements; however, they serve as parent nuclides of radioactive decay series that include isotopes with physical and chemical properties similar to those of other elements. Many of these isotopes exhibit elevated gamma activity, making it possible to indirectly detect the presence of associated chemical elements [[1], [2]]. During migration through structurally weakened zones, such as fault systems, oxidation zones, and weathering crusts, these isotopes form dispersion haloes that are commonly associated with ore-related elements. The identification and interpretation of such haloes can facilitate the recognition of their source zones and, ultimately, concealed ore bodies [2]. Combined with a comprehensive assessment of ore body characteristics, this approach may provide a basis for the future application of artificial intelligence technologies in solid mineral exploration.

Drawing on extensive geological exploration experience, JSC Volkovgeology maintained a specialized geological team that collaborated with various scientific and industrial organizations. The primary objective of this team was to provide scientific support for uranium prospecting throughout its area of operation.

In addition, a regional prospecting team was responsible for collecting and analyzing current information on uranium occurrences, supervising prospecting activities, evaluating the quality of exploration work, and providing technical support. Similar prospecting groups operated within individual expeditions, carrying out equivalent tasks within their designated territories. These exploration teams constituted the primary operational units of uranium prospecting. Comparable thematic teams and groups were also involved in the exploration of other mineral resources. At the same time, petroleum geologists and hydrogeologists conducted their activities independently from other geological services in Kazakhstan. Collectively, these efforts contributed to the establishment of a mineral resource base that has supported the country's needs for decades. However, further expansion and reassessment of this resource base have now become increasingly important.

The activities of thematic exploration teams were organized according to the standard stages of geological investigation, including reconnaissance, prospecting, evaluation, and detailed exploration. Each stage involved a specific set of tasks, such as geological surveying, compilation and analysis of previous exploration results, resource assessment, and planning of subsequent exploration activities.

Field teams prepared exploration programs and work plans, carried out field investigations, and produced technical reports, geological maps, and resource and reserve estimates. All activities were conducted in accordance with the requirements of the corresponding exploration stage. Recent developments in digital technologies and artificial intelligence have created a need for the systematic formalization and digitization of accumulated geological and related datasets. This includes the processing of digital information, the development of analytical algorithms, and the creation of decision-support systems capable of translating complex digital data into interpretable geological knowledge [[3], [4]].

This study aims to evaluate the role of natural radioactivity as an exploration indicator for rare-metal, gold, and polymetallic mineralization in Eastern Kazakhstan and to assess its significance as a source of potential radioecological hazards.

The objectives of the study include analyzing the distribution of radionuclides in bottom sediments, identifying anomalous zones through factor analysis, and evaluating their relationship with regional metallogenic structures.

In addition, the study considers the potential application of modern digital and analytical methods for processing geological and radiometric data as a promising direction for future research [5].

Materials and Methods

Data source. The present study is based on the results of regional radiohydrolithogeo-chemical surveys conducted across Kazakhstan at a scale of 1:1,000,000. In Eastern Kazakhstan, field sampling and laboratory analyses were carried out between 1991 and 1994.

Although the surveys were originally designed to assess the radioecological state of the environment, the resulting dataset contains information not only on radionuclides but also on ore-related chemical elements. Consequently, these data can be effectively applied to geological and metallogenic investigations.

To date, a national geochemical database has been established, comprising approximately 18,000 sampling sites and analytical results for an average of 25 chemical components per sample. Based on these data, a series of digital maps depicting the distribution of radioactive and geochemical contaminants in bottom sediments and natural waters has been developed for all regions of Kazakhstan.

The surveys were conducted within the framework of the State Program 011, "Ensuring Radiation Safety," which was aimed at evaluating the radiation situation throughout the territory of the Republic of Kazakhstan [[6], [7]].

Sampling design. The survey was conducted using a microbasin-based approach, whereby each sampling site reflects the integrated geochemical signature of its corresponding drainage basin [8].

Sampling was primarily carried out at the mouths of small rivers and streams. The average area of the investigated microbasins was approximately 120 km², with individual basin areas ranging from 80 to 150 km². In regions characterized by well-developed endorheic drainage systems, bottom sediment samples were collected from lakes. In dry stream channels, samples were taken from the lowest sections of the channel beds, where fine-grained material tends to accumulate.

In low-relief terrain, composite samples were collected from 10 × 10 m plots. Each composite sample consisted of five subsamples obtained from the four corners and the center of the sampling area. Quality-control samples accounted for approximately 5% of the total number of collected samples.

Field observations included the description of sediment grain size, color, and the presence of organic matter.

Sample preparation and analytical methods. Bottom sediment samples were air-dried and prepared according to standard laboratory procedures. From each initial sample weighing 5–6 kg, a representative subsample of approximately 0.7–0.8 kg (particle size fraction < 3 mm) was selected for analytical determination.

Gamma-ray spectrometric measurements were performed to determine the activities of Ra-226, Ra-228, Th-232, and K-40 using a Canberra gamma spectrometer equipped with a high-purity germanium detector [9]. The relative analytical uncertainty at background activity levels was approximately 30%. The corresponding detection limits were as follows:

- Ra-226: 20 Bq/kg
- Ra-228: 40 Bq/kg
- Th-232: 40 Bq/kg
- K-40: 100 Bq/kg

The concentrations of uranium, thorium, Pb, As, and Se were additionally determined by X-ray fluorescence analysis using an ARF-6 spectrometer. The detection limits were:

- U: 0.4 mg/kg (approximately 4.0 Bq/kg)
- Th: 1.0 mg/kg (approximately 4.1 Bq/kg)
- Pb: 0.001%
- Se: 0.001%
- As: 0.002%

Although more advanced analytical techniques, such as inductively coupled plasma mass spectrometry (ICP–MS), are currently available, the present study is based on archived datasets obtained using the analytical methods described above.

Data selection. For the present study, only bottom sediment samples were considered. Five naturally occurring radionuclides were selected as the primary indicators: U-238, Ra-226, Th-232, Ra-228, and K-40.

These radionuclides were used as geochemical indicators of geological processes and ore-forming environments. Their distribution patterns provide valuable information on the migration and accumulation of radioactive elements and may reflect the influence of lithological, structural, and metallogenic factors.

Data processing and interpretation. The analysis was based on factor analysis using the principal component method applied to radionuclide and associated geochemical datasets [[10], [11]]. Factor analysis was employed to:

- identify anomalous geochemical associations;
- reduce the dimensionality of the dataset;
- reveal spatial patterns in radionuclide distribution.

The extracted factors were interpreted in terms of geological processes and subsequently compared with the distribution of known metallogenic zones.

Spatial analysis included the comparison of identified anomalous areas with major ore-bearing regions of Eastern Kazakhstan, particularly the Rudny Altai and Kalba–Narym metallogenic zones.

The study focuses on regional-scale interpretation and the assessment of spatial relationships between radionuclide anomalies and mineralization patterns rather than on the re-evaluation of primary analytical data.

Results

The boundaries of the identified radiogeochemical zones and the locations of major radioactive sites at a scale of 1:1,000,000 are presented on regional radiation intensity maps. The radiological characteristics of individual radioactive sites and radiogeochemical zones are documented in the radiation-hygienic passports of the corresponding oblasts. These datasets provide an important basis for the development of a national radiation monitoring system in the Republic of Kazakhstan.

In addition to their application in radiation safety assessment, radiohydrolithogeochemical survey data can also be used for the exploration of non-radioactive solid mineral resources.

Within the study area, several radiogeochemical anomalies were identified in the Kalba–Narym and Rudny Altai regions. These anomalies are associated with elevated concentrations of Ra-226 in bottom sediments, as well as with radioactive waste dumps and natural radon sources [7].

The average annual effective radiation doses for the population were estimated as follows:

• Kalba–Narym region: 3.6 mSv/year (Ulan site), 4.1 mSv/year (Bukhtarma site), and 4.5 mSv/year (Kurchum site);

• Rudny Altai region: more than 6.7 mSv/year (Leninogorsk site) and 3.7 mSv/year (Rakhmanovskie Klyuchi site).

Studies of indoor radon exposure in residential areas yielded the following average annual effective doses:

• 2.4 mSv/year in Ust-Kamenogorsk;
• 6.3 mSv/year in Ulansky District;
• 5.0 mSv/year in Kokpektinsky District;
• 4.1 mSv/year in Kurchumsky District.

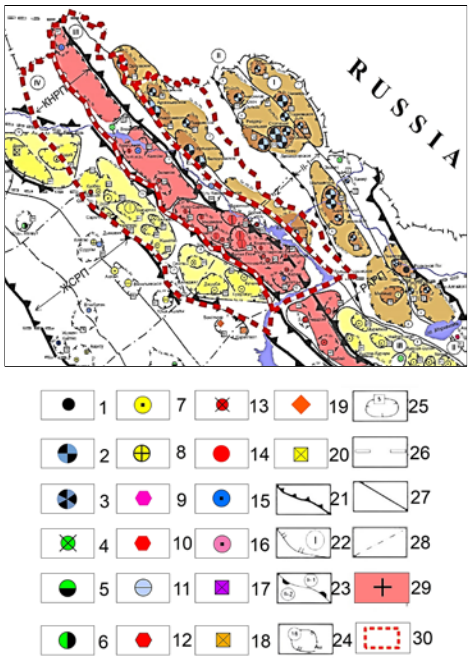

Figure 1 - Scheme of zoning of ore belts and metallogenic zones of the Greater Altai [12]. Geological and industrial types of deposits: 1 - hematite-magnetite volcanogenic-sedimentary (Kholzunsky); 2-copper-coal (ore-altai); 3-lead-zinc (South- Altai); 4-copper-pyrrhotite (Karchiginsky); 5-copper-porphyry (Kyzylkainsky); 6-copper-nickel sulfide (Maksutsky); 7-gold-quartz (Kuludzhunsky); 8-gold-myshyakovite-carboniferous (Bakyrchiksky); 9-epimagmatic niobium-zirconium-rare earth (Upper Espinsky); 10-pegmatitic rare-metal (Kalbinsky); 11-skarnovo-greisen-tungsten; 12-albitite-greisen tin-tantalum (Karasu type); 13-greisen-quartz-quartz vein stockwork tin (Cherdoyak type); 14-greisen-quartz-quartz vein tin; 15- tungsten and 16- molybdenum; 17-silicate cobalt-nickel (Gornostayevsky); 18- zircon-ilmenite weathering crust (Karaotkel type); 19- alluvial (Satpayevsky); 20-gold-alluvial (Suzdal); 21-boundaries of ore belts: Rudno-Altaisky (RARP), Kalba-Narymsky (KNRP), Zapadno-Kalbinsky (ZKRP), Zharma-Saursky (ZhSRP); 22-boundaries of metallogenic zones and their numbers: I - Beloubinsko-Sarymsaktinskaya, III - Rudnoaltayskaya, IIIII - Irtyshskaya, IV - Kalba-Narymskaya, V - Zapadno-Kalbinskaya, VII - Charskaya, VII - Zharma-Saurskaya, VIII - Sirektas-Sarzanskaya; 23 - boundaries of metallogenic subzones and their numbers: III-1-Leninogorsk-Zyryanovskaya, III-2-Priirtyshskaya; 24- known and potential (dotted) ore districts, their numbers; 25- known and potential ore nodules, their numbers; 26- deep latitudinal faults of ancient emplacement; 27-deep north-western faults limiting metallogenic zones; 28-northeastern block and cliff faults; 29-granitoids of Kalba-Narym pluton (Kalbinsky complex, P_{1}); 30-contours of ore subzones included in the 2025 Scientific Research Program. (The map is presented at a regional scale corresponding to 1:1,000,000).

These results indicate generally higher radiation exposure levels in rural areas than in urban environments.

A comparison of the factor-analysis results with the geotectonic and metallogenic zoning pattern of the Greater Altai reveals a spatial relationship between radiogeochemical anomalies and major ore-bearing structures [12].

According to the metallogenic zoning scheme of the Greater Altai (Fig. 1), twenty geological-industrial deposit types have been identified. Among them, three principal groups are of particular economic importance:

• polymetallic (Cu–Pb–Zn), iron-polymetallic, and copper-gold deposits;

• gold-quartz and related gold-bearing deposits;

• rare-metal deposits.

Pyrite polymetallic type. The pyrite-polymetallic type of mineralization, which is widespread throughout the Rudny Altai metallogenic zones (I–III), is commonly associated with gold, silver, and various rare metals [13].

Secondary geochemical dispersion haloes of uranium and thorium have been identified in association with these ore deposits (Figs. 2 and 3).

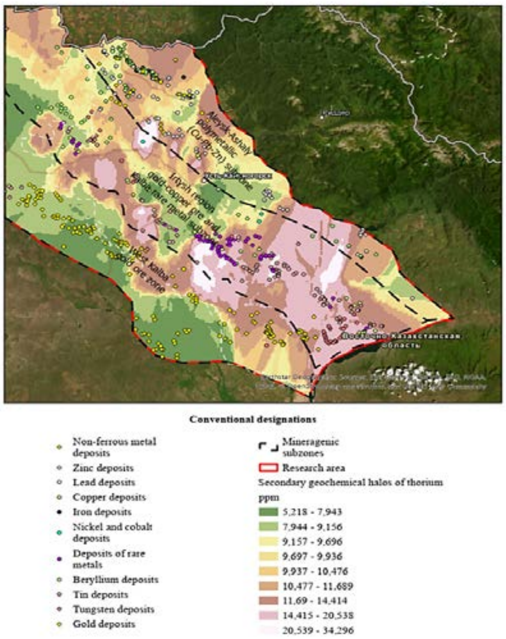

Figure 2 - Secondary geochemical halos of thorium. Spatial distribution of thorium (ppm) in bottom sediments. Color gradations represent concentration ranges, while symbols indicate mineral deposits of various types. The red boundary outlines the study area, and mineralogenic subzones are shown. The map reflects the regional survey scale of 1:1,000,000 used in the study.

Based on their gold and silver contents, the deposits can be classified into three groups:

• high-gold (1–5 g/t) and moderate-silver (20–85 g/t) deposits;

• moderate-gold (0.3–1.3 g/t) and relatively silver-rich (35–120 g/t) deposits;

• deposits characterized by low concentrations of both gold and silver.

Factor analysis of the bottom sediment dataset identified twelve anomalous sites characterized by three to five significant factors, with cumulative explained variance ranging from 62.8% to 83.6%. These values indicate that the adopted factor model adequately represents the structure of the dataset and provides a reliable basis for interpreting the spatial distribution of radionuclides and associated geochemical elements.

The first two anomalous sites (Fig. 4) are located within the Rudny Altai region and coincide with known uranium-bearing zones.

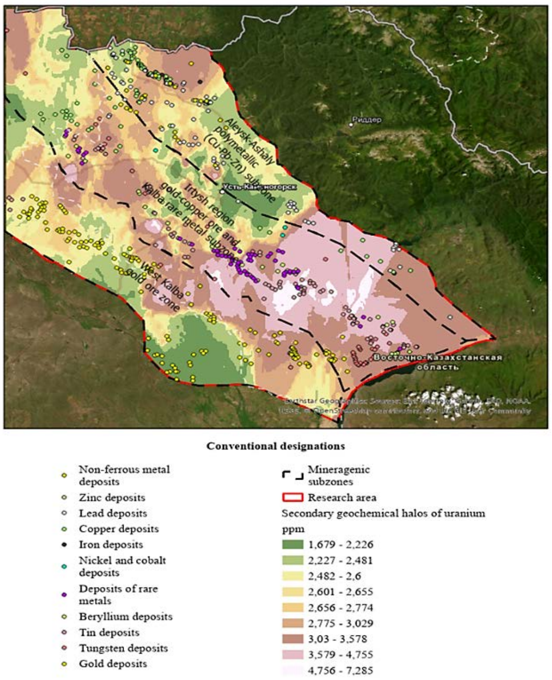

Figure 3 - Secondary geochemical halos of uranium. The map shows the spatial distribution of uranium concentrations (ppm) in bottom sediments, classified by intensity. Color gradations represent concentration ranges, while symbols indicate mineral deposits of various types. The red boundary outlines the study area, and mineralogenic subzones are shown. The map reflects the regional survey scale of 1:1,000,000 used in the study.

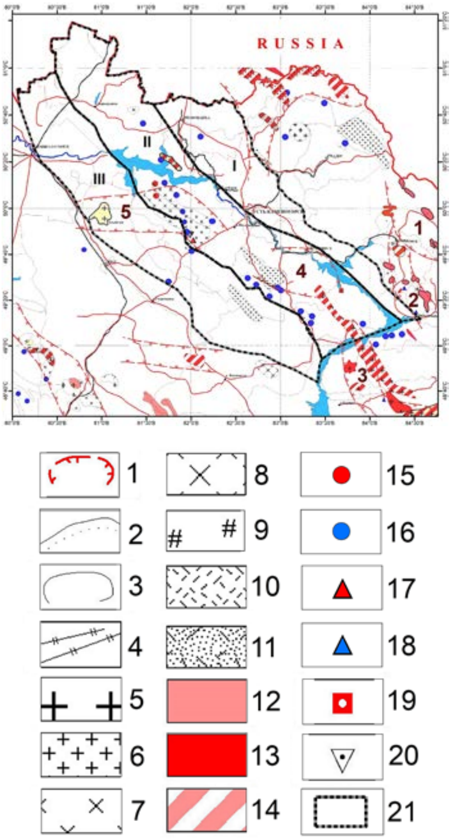

Figure 4 - Anomalous radiogeochemical sites identified by factor analysis in the microbasins of bottom sediments of Eastern Kazakhstan. Sites 1–2 are located within the Rudny Altai zone, while sites 3–5 correspond to the Kalba-Narym rare-metal zone. The map includes geological boundaries, mineral occurrences, and anomalous zones of uranium and thorium distribution. The inset shows the location of the study area within Kazakhstan. The map reflects the regional survey scale of 1:1,000,000 used in the study [6].

Gold type. Gold mineralization is widely distributed in the western and southeastern parts of the Kalba–Narym metallogenic zone. The distribution patterns and geological characteristics of gold deposits in Eastern Kazakhstan have been comprehensively described in regional geological studies and reference publications [20].

Within the gold-bearing zones, reduced activities of uranium and thorium are generally observed, whereas the activities of Ra-226 and Ra-228 remain close to regional background levels. This observation is consistent with the absence of significant uranium and thorium anomalies within these areas.

At the same time, elevated levels of natural radioactivity may occur due to the contribution of other radionuclides, particularly K-40.

Although gold and uranium are not generally considered genetically related, correlation analysis between gold concentrations and radionuclide activities may enhance the effectiveness of gamma-spectrometric methods in mineral exploration.

This relationship is supported by studies conducted at the Malomyrskoye deposit, where statistically significant correlations between radioactivity parameters and gold concentrations were identified.

To evaluate these relationships, correlation analysis [14] was performed between gold content and the activities of several radionuclides, including potassium-40 (40K), cesium-137 (137Cs), radium isotopes (226Ra, 228Ra, and 224Ra), radon (222Rn), and thorium-232 (232Th).

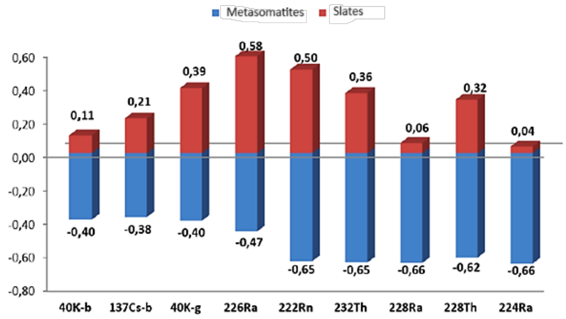

Figure 5 - Correlation coefficients (R) between gold content and radioisotope activity (40K, 137Cs, 226Ra, 222Rn, 232Th, 228Ra, 224Ra). Positive and negative correlations are shown.
Significant values at $p < 0.05$ are indicated

Rare metal type. The Kalba–Narym rare-metal metallogenic zone is characterized by granitoid magmatism and associated mineralization, including Sn, W, Ta, and Nb deposits [15].

The results of factor analysis (Table 1) indicate that anomalous sites 3, 4, and 5 spatially coincide with this metallogenic zone. This spatial relationship suggests a possible association between radionuclide distribution patterns and rare-metal mineralization.

Table 1 presents the results of factor analysis for radionuclides and associated chemical elements in bottom sediments. The obtained factor structure reflects the relationships between radionuclides and geochemical elements within the sedimentary environment.

Positive factor loadings indicate the co-occurrence and accumulation of elements controlled by common geochemical processes. In contrast, negative loadings may reflect contrasting behavior, including element separation, migration, or depletion under conditions of oxidation, weathering, and transport.

The identified factor associations allow the recognition of geochemical patterns characteristic of ore-forming environments and provide a basis for interpreting anomalous sites in relation to potential mineralization processes.

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Table 1 - Results of factor analysis of radionuclides and associated chemical elements in bottom sediments of Eastern Kazakhstan

Anomalous site number	Parameters of factors	Factor 1		Factor 2		Factor 3		Factor 4		Factor 5	
		Positive correlation	Negative correlation	Positive correlation	Negative correlation	Positive correlation	Negative correlation	Positive correlation	Negative correlation	Positive correlation	Negative correlation
1 RA		K40 U238 Th232 Pb	Ra228 Cs137	Ra228 Th232 Pb	As Cs137 K40 Se	Se	As K40 Cs137 Ra226	Ra226 Th232	As Pb Se Cs137	Cs137	As U238 Se Ra228
	% of variance	26.1		16.6		14.8		13.5		12.6	
	cumulative %	26.1		42.7		57.5		71.0		83.7	
2 RA		U238 Cs137	Se Ra228 Ra226	K40 Ra226 Ra228 U238	Pb	Th232 Pb Ra226	Ra228 K40 U238		Th232		
	% of variance	24.3		20.0		19.6		16.7			
	cumulative %	24.3		44.3		63.9		80.6			
3 KN		Th232 Pb Ra228 U238	Cs137	Ra226 Cs137 U238	K40 Se Th232	Se Ra228	K40 U238 Cs137	As Pb Se	Ra228 Ra226		
	% d of variance	27.0		21.4		13.1		12.9			
	cumulative %	27.0		48.4		61.5		74.4			
4 KN		Ra228 Th232 Pb Ra226	As Cs137	As Ra226	Cs137 Ra228	Cs137 K40 Ra226	Se Th232 As U238				
	% of variance	26.1		18.8		18.7					
	cumulative %	26.1		45.0		63.7					
5 KN		Th232 U238 Pb	As Se Cs137 K40	Ra228 Se	Ra226 Th232 As	K40 Pb	U238 Ra226 Ra228 Cs137	Cs137 Pb As	Ra226 U238 K40 Se	Ra226 As	Th232 K40 Se Ra228
	% of variance	20.5		17.8		15.4		15.1		14.5	
	cumulative %	20.5		38.3		53.6		68.7		83.2	

Rare earth type. Rare earth element exploration in Kazakhstan is currently receiving increasing attention due to the implementation of the Concept for the Development of the Geological Industry of the Republic of Kazakhstan for 2023–2027 and the Comprehensive Plan for the Development of the Rare and Rare-Earth Metals Industry for 2024–2028.

According to recent geological assessments, at least 15 rare earth element occurrences and deposits have been identified in different regions of Kazakhstan [20]. The revealed patterns of radionuclide distribution and their associations with ore-related chemical elements may contribute to the identification of new prospective areas and improve approaches for rare earth element exploration.

Discussion

The obtained results demonstrate that natural radioactivity can be considered not only as an indicator of environmental conditions but also as a valuable exploration criterion for various types of mineralization in Eastern Kazakhstan [16].

The identified anomalous zones, established through radiohydrolithogeochemical surveys and factor analysis, show a clear spatial association with major metallogenic structures of the Greater Altai region [13]. In particular, polymetallic mineralization of the Rudny Altai and rare-metal mineralization of the Kalba–Narym zone are characterized by elevated concentrations of uranium and thorium and the presence of their secondary geochemical dispersion haloes.

In the Rudny Altai region, the association between polymetallic mineralization and radioactive elements may be related to ore-forming processes involving volcanogenic-sedimentary sequences and granitoid complexes. The occurrence of uranium-bearing zones and uranium–thorium geochemical anomalies supports the use of radioactive elements as indicators of ore-forming environments [17].

In contrast, gold-bearing zones are characterized by reduced uranium and thorium activities, whereas radium isotopes generally remain at background levels. This suggests that gold mineralization is not directly genetically associated with uranium; however, indirect relationships may occur through common geological and geochemical processes. The analysis of correlations between radionuclide activities, including K-40, and gold concentrations may improve the efficiency of gamma-spectrometric approaches in mineral exploration.

This interpretation is supported by investigations of the Malomyr gold deposit, where statistically significant relationships between radioactivity parameters and gold content were identified. Such relationships may contribute to a more reliable assessment of the mineral potential of geological sections.

For the Kalba–Narym rare-metal zone, the spatial coincidence of radiogeochemical anomalies with granitoid complexes and rare-metal mineralization (Sn, W, Ta, Nb, and rare earth elements) indicates a close relationship between thorium-enriched geological environments and rare-metal mineralization. This association can be explained by the similar geochemical behavior of thorium and rare earth elements, including comparable ionic characteristics and their distribution during magmatic and hydrothermal processes. This interpretation is consistent with studies of rare-metal and rare-earth mineralization related to alkaline granitoid systems [18].

The results highlight the dual significance of natural radioactivity. On the one hand, radioactive anomalies provide important information on ore-forming processes and can be applied in the exploration of rare-metal, noble-metal, and polymetallic deposits. On the other hand, elevated radioactivity levels may represent a potential environmental and health risk that should be considered during exploration and mining activities.

It should be noted that this study is based on archived regional datasets; therefore, further investigations using modern analytical techniques and digital approaches are required to refine the identified relationships. The integration of radiohydrolithogeochemical data with geographic information systems (GIS) and advanced data-processing methods may significantly improve the efficiency of mineral prospecting and resource assessment [19].

Conclusions

The major geological-industrial types of mineral deposits in Eastern Kazakhstan associated with elevated radioactivity demonstrate spatial relationships with the Rudny Altai and Kalba–Narym linear structures, as well as with the Irtysh suture zone.

Granite complexes related to these tectonic structures, particularly within the Kalba–Narym rare-metal zone and partly within the Rudny Altai and Irtysh zones, are characterized by increased levels of natural radioactivity.

Uranium-thorium mineralization is mainly associated with acidic intrusive complexes of subalkaline to alkaline composition of Permian, Triassic age, whereas rare-earth mineralization is commonly related to alkaline granite complexes.

Gold deposits of the Mukur, Bakyrchik, and Kuludzhun ore districts are characterized by relatively low uranium and thorium contents and elevated Ra-226 activities compared with regional background values.

Deep-seated faults play an important ore-controlling role, reflecting the influence of hydrothermal processes and acting as potential pathways for the migration of ore-forming fluids. The application of modern analytical methods, including spectral, chemical, X-ray, mass spectrometric, and X-ray fluorescence techniques, expands the capabilities for mineral deposit investigation and improves the reliability of geochemical interpretation.

The incorporation of radioactivity parameters and natural isotope associations into exploration criteria can enhance the efficiency of prospecting for rare-metal, gold, and polymetallic deposits. At the same time, elevated radioactivity associated with rare-metal, rare-earth, and uranium mineralization highlights the importance of radiation safety considerations during exploration and mining activities, including the protection of personnel and the environment.

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Шығыс Қазақстандағы сирек жер элементтері, алтын және полиметалл кен орындарын іздеудің белгісі ретінде радиоактивтілік және осы кен орындарын игеру кезінде радиациялық-экологиялық қауіптің жоғары деңгейінің индикаторы

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ТҮЙІНДЕМЕ
Бұл зерттеу Шығыс Қазақстандағы сирек металды, алтын және полиметалл минералдануы үшін табиғи радиоактивтіліктің іздеу белгісі ретіндегі рөлін, сондай-ақ оның радиоэкологиялық қауіп факторы ретіндегі маңызын бағалауға бағытталған. Талдау 1:1 000

000 масштабында жүргізілген аймақтық радиогидролитохимиялық түсірілімдердің нәтижелеріне негізделген және микробассейндер шегінде түптік шөгінділерден сынама алуды қамтиды. Зерттеу негізгі табиғи радионуклидтерге (U-238, Ra-226, Th-232, Ra-228, K-40) және олардың кеңістіктік таралуына бағытталған. Аномальды геохимиялық ассоциацияларды анықтау және олардың металлогендік құрылымдармен байланысын бағалау үшін факторлық талдау қолданылды. Нәтижесінде Қазақстан аумағында 80 әлеуетті радиоэкологиялық қауіпті аймақ анықталды, оның ішінде 5 аймақ Шығыс Қазақстанда орналасқан. Зерттелген аумақта 12 аномальды учаске белгіленді, олар 3–5 фактормен сипатталады, ал жиынтық түсіндірілген дисперсия 62,8%-дан 83,6%-ға дейін өзгереді. Анықталған аномалиялар негізгі металлогендік аймақтармен, әсіресе полиметалл және сирек металды минералданумен байланысты Рудный Алтай және Калба-Нарым өңірлерімен кеңістіктік сәйкестік көрсетеді. Нәтижелер табиғи радиоактивтіліктің тиімді іздеу белгісі әрі экологиялық қауіп факторы бола алатынын дәлелдейді. Зерттеу радиоактивтілік параметрлерін іздеу критерийлеріне енгізудің әлеуетін көрсетеді және геологиялық барлау мен тау-кен жұмыстарын жүргізу кезінде радиациялық қауіпсіздікті ескеру қажеттігін атап өтеді.

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Радиоактивность как поисковый признак месторождений редких земель, золота и полиметаллов Восточного Казахстана и индикатор повышенного уровня радиоэкологической опасности при разработке этих месторождений

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АННОТАЦИЯ
Данное исследование направлено на оценку роли естественной радиоактивности как поискового признака редкометальной, золоторудной и полиметаллической минерализации Восточного Казахстана, а также её значения как фактора радиоэкологической опасности. Анализ основан на результатах региональных радиогидролитохимических съёмок, выполненных в масштабе 1:1 000 000, включая отбор проб донных отложений в пределах микробассейнов. Основное внимание уделено ключевым природным радионуклидам (U-238, Ra-226, Th-232, Ra-228, K-40) и их пространственному распределению. Для выявления аномальных геохимических ассоциаций и оценки их связи с металлогеническими структурами был применён факторный анализ. В результате на территории Казахстана было выделено 80 потенциально радиоэкологически опасных зон, из которых 5 расположены в Восточном Казахстане. В пределах исследуемой территории выявлено 12 аномальных участков, характеризующихся 3–5 факторами с суммарной объяснённой дисперсией от 62,8% до 83,6%. Выявленные аномалии демонстрируют пространственное соответствие основным металлогеническим зонам, прежде всего Рудного Алтая и Калба-Нарымского региона, ассоциированных с полиметаллической и редкометальной минерализацией. Полученные результаты показывают, что естественная радиоактивность может служить как эффективным поисковым признаком, так и важным фактором экологического риска. В работе показан потенциал включения параметров радиоактивности в систему поисковых критериев, а также подчёркивается необходимость учёта радиационной безопасности при проведении геологоразведочных и горных работ.

Ключевые слова: радиоактивность, поисковый признак, гамма-спектрометрия, уран, торий, рудные месторождения

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