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CRITERIA OF RARE-METAL ORE POTENTIAL AND THEIR APPLICATION IN PREDICTING PROSPECTIVE AREAS (A CASE STUDY OF THE KALBA-NARYM BELT)

Abstract. The paper summarizes studies of the Kalba-Narym Belt of the Altai accumulated over more than 70 years of research into the ore potential of rare-metal granites. Ore-formation features of rare-metal mineralization are analyzed, and key groups of ore indicators and criteria are identified. Metallogenic zoning was used to delineate prospective areas for discovering new occurrences and assessing the potential of known deposits. Source materials were systematized into a database of 280 occurrences and deposits integrated into the ArcGIS geospatial environment using regional geophysical data and remote sensing (Landsat, Sentinel-2). Machine learning improves the reliability of predictive modeling.
Key words: *rare metals, Kalba-Narym Belt, metallogenic zoning, formation types, magmatic criteria, Sentinel-2.*

Сирек металдардың рудалылық критерийлері және оларды перспективалы аумақтарды болжауда қолдану (Қалба-Нарым белдеуі мысалында)

Аңдатпа. Мақалада Алтайдағы Қалба-Нарым белдеуі бойынша сирекметалды граниттердің рудалылығын зерттеудің 70 жылдан астам уақыт ішінде жинақталған нәтижелері қорытындыланған. Сирекметалды минералдану көріністерінің рудно-формациялық ерекшеліктері қарастырылып, негізгі белгілер мен рудалылық критерийлері айқындалған. Металлогендік аудандастыру негізінде жаңа нысандарды анықтауға және белгілі кен орындарының әлеуетін бағалауға перспективалы аумақтар бөлінген. Бастапқы материалдар 280 нысанды қамтитын деректер базасына жүйеленіп, ArcGIS геоақпараттық ортасына геофизикалық және ЖҚЗ (Landsat, Sentinel-2) деректерімен біріктірілген. Машиналық оқыту болжам нәтижелерінің сенімділігін арттырады.
Түйінді сөздер: *сирек металдар, Қалба–Нарым белдеуі, металлогендік аудандастыру, формациялық типтер, магмалық критерийлер, Sentinel-2.*

Критерии рудоносности редких металлов и их использование при прогнозировании перспективных площадей (на примере Калба-Нарымского пояса)

Аннотация. Обобщены результаты исследований Калба-Нарымского пояса Алтая, накопленные за более чем 70-летний период изучения рудоносности редкометальных гранитов. Рассмотрены рудно-формационные особенности проявлений редкометальной минерализации, выделены основные группы признаков и критериев рудоносности. На основе металлогенического районирования определены перспективные площади для выявления новых объектов и оценки потенциала известных месторождений. Исходные материалы систематизированы в базе данных (280 проявлений и месторождений), интегрированной в геопространственную среду ArcGIS с привлечением региональных геофизических данных и материалов ДЗЗ (Landsat, Sentinel-2). Применение методов машинного обучения повышает достоверность прогнозных построений.
Ключевые слова: *редкие металлы, Калба-Нарымский пояс, металлогеническое районирование, формационные типы, магматические критерии, Sentinel-2.*

Introduction

The Kalba-Narym belt represents one of the most important rare-metal provinces, encompassing several deposits (Bakennoe, Belogorskoe, Yubileinoe, Akhmetkino, Medvedka, Tochka, Cherdoyak, etc.), which constitute the core of the rare-metal mineral resource base of the Republic of Kazakhstan in terms of light lithophile elements (***Be***, ***Rb***, ***Cs***, ***Li***), as well as a significant portion of the resource base for heavy lithophile elements (***Ta***, ***Nb***, ***W***, lanthanides) and tin (***Sn***).

From a geotectonic point of view, the Kalba-Narym belt is a fragment of Gondwana, which joined the Siberian paleocontinent as a result of the Hercynian collision [1, 2]. In post-collision conditions, a stretching environment was created along the emerging Zaisan rift with orogeny in adjacent territories, with powerful granite magmatism and shear tectonics (Figure 1).

Granites of the Kalba-Narym belt have been studied in detail since the 1930s, initially as sources of tin mineralization. From the 1950s onward, geological exploration focused on the search for deposits of tantalum-niobates, beryllium, and cesium. Such a prolonged period of investigation has resulted in the accumulation of a substantial body of data on various aspects of the metallogeny of the Kalba-Narym belt; approximately 300 occurrences and indications of rare-metal mineralization have been identified (Figure 2). In addition to comprehensive monographs [2, 3, 5, etc.], significant contributions have been made by geological re-evaluation and thematic reports of the 1970s–1990s, dedicated to reassessing the potential of individual deposits and ore clusters.

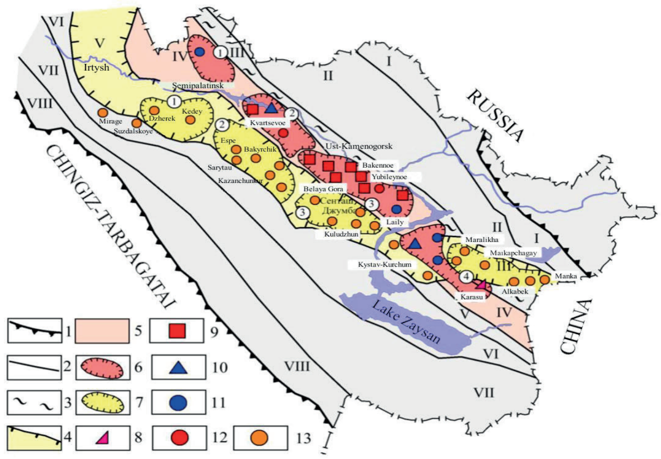
Methods and materials

Ore-Formation and Metallogenic Zoning of the Kalba-Narym Belt

The Kalba-Narym belt is underlain by the eponymous pluton, a magmatic body extending over more than 500 km in length and up to 50 km in width, composed of individual massifs that are interconnected at the surface or at depth. According to gravimetric data, the pluton corresponds to a regional negative gravity anomaly with an amplitude of 13–32 mGal, complicated by local anomalies associated with individual intrusive bodies [1, 2].

According to the scheme of V. V. Lopatnikov [3] the following sequence of magmatic intrusions has been established: the plagiogranite-granodiorite formation, ranging in composition from gabbro to plagiogranites (Kunush Complex, C_{2-3}); the Kalguty rhyolite-dacite formation (C_3); the Kalba granite-granodiorite complex (P_1); the granite-leucogranite formation (Monastyr Complex, P_2 – T_1). Several researchers additionally distinguish a dyke complex of gabbro-diabase-granite porphyry composition (Mirolyubov Complex, T_1) [5, 6].

The rare-metal specialization of the Kalba-Narym belt is primarily associated with the granites of the Kalba Complex;



1 – boundaries of the Greater Altai; 2 – boundaries of metallogenic zones; 3 – Irtysh shear zone; 4 – boundary of the gold belt; 5 – Kalba-Narym belt.
6 – ore districts of the Kalba-Narym Belt:
1 – Shulbinsky, 2 – North-West Kalba, 3 – Central Kalba, 4 – Narym;
7 – ore districts of the West Kalba gold belt:
1 – Mukur, 2 – Bakyrchik, 3 – Kuludzhun, 4 – South Altai;
8–13 – deposits:
8 – albitite-greisen (Sn, Ta); 9 – rare-metal pegmatites (Ta, Nb, Be, Li, etc.); 10 – greisen–quartz vein (Sn, W); 11 – hydrothermal quartz-vein (Sn, W); 12 – tin; 13 – gold.
Metallogenic zones:
I – Beloubinsk–Sarymsaktin, II – Rudny Altai, III – Irtysh, IV – Kalba–Narym, V – West Kalba, VI – Char, VII – Zharma–Saur, VIII – Sirektas–Sarsazan

Figure 1. Spatial distribution of the Kalba-Narym Belt and the West Kalba gold belt within the Altai structural framework, combined with the metallogenic zoning of the Kalba-Narym Belt, after [1, 2].
Сурет 1. Алтай құрылымындағы Қалба-Нарым белдеуі мен Батыс Қалба алтын белдеуінің орналасу сызбасы, Қалба-Нарым белдеуінің металлогендік аудандастырылуымен бірге көрсетілген [1, 2] бойынша.
Рис. 1. Схема размещения Калба-Нарымского пояса и Западно-Калбинского золоторудного пояса в структуре Алтая, совмещенная с металлогеническим районированием Калба-Нарымского пояса, согласно [1, 2].

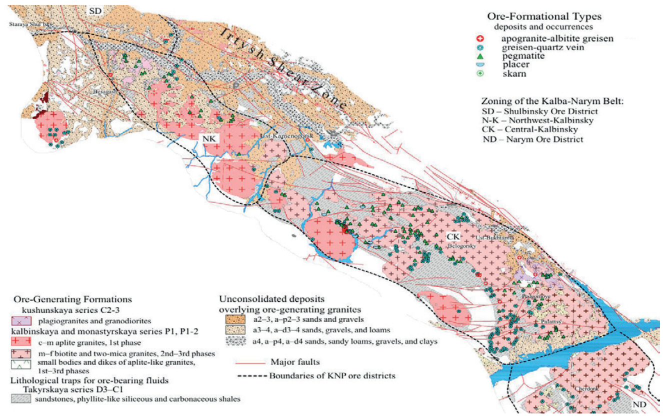


Figure 2. Distribution areas of granites of the Kalba-Narym Belt (KNB) and associated rare-metal mineralization occurrences.
Сурет 2. Қалба-Нарым белдеуінің (ҚНБ) граниттерінің таралу аймақтары және олармен байланысты сирекметалды минералдану нысандары.
Рис. 2. Области развития гранитов Калба-Нарымского пояса (КНП) и связанные с ними объекты редкометальной минерализации.

however, rare-metal enrichment is also characteristic of the Kalguty, and Monastyr complexes. Several pegmatite deposits (Akhmetkino, Tochka, Medvedka, etc.) are also hosted within ore-localizing dykes of plagiogranites and granite porphyries of the Kunush Complex.

The lateral heterogeneity of the Kalba-Narym Belt structure has allowed the identification of four megablocks along the belt's main NW–SE elongation. These blocks also correlate with the predominant ore-formational characteristics of the deposits [2, 7] and can be briefly described as follows:

Shulbinsky District is located on the outermost north-western flank of the Kalba-Narym Belt and is largely covered by a cover of unconsolidated sediments. According to geological-geophysical reconstructions by Lyubetsky [10], the belt exhibits a significant widening (up to 90 km). Several large granite massifs have been identified (Shulbinsky, Kozhankul, Bekovsky, etc.), mostly covered by loose sediments. Prospects are associated with potentially ore-bearing ***Li–F*** granites, tin-bearing dykes, direct evidence of rare-metal mineralization (***W***, ***Sn***), numerous zones of silicification in the host sedimentary rocks, and geochemical anomalies of ***W***, ***Sn***, ***Be***, ***Nb***, ***Bi***, ***As***, ***Cu***, and ***Au***.

The North-Western District. Monastyr and Kalba granites are widely developed among the enclosing sandy-black shale strata. Quartz veins are widely distributed within the sedimentary rocks. Quartz-vein deposits (***Sn***, ***W***, ***Sn-W***, ***Sn-Au***) and rare-metal pegmatitic occurrences (***Ta***, ***Nb***, ***Be***, ***Li***, etc.) are roughly equally represented [4, 5].

Central District. Granites of the Kalba Complex strongly dominate, while the Monastyr series is poorly developed. At the district margins, Kunush plagiogranites with a vein pegmatitic series specialized in rare metals are present. Among host intrusive rocks, the Takyr series of carbonaceous black shales is most widespread. Pegmatite occurrences are primarily concentrated in the apical parts of Kalba intrusions; at the periphery, quartz veins in Kalba granites and host sequences, as well as pegmatitic vein-like bodies in the Phase II Kunush series, are common. Over 90% of pegmatite deposits are concentrated in the Central District, with apogranitic greisen-quartz vein and greisen occurrences featuring ***Ta-Sn***, ***Ta-Nb-Be***, and ***Li-Cs*** mineralization [6, 7]. Sn and W mineralization is limited to the peripheral parts of the district and occurs on a relatively small scale.

Narym District. Kalba granites are widely developed, while Monastyr granites are completely absent. Vein-type rocks are extensively represented. Numerous isolated stocks and small dyke-like bodies of granitoids of the Kalguty association, as well as extensive belts of porphyritic dykes, have been documented [3]. Linear zones and fields of quartz veins with ***Sn***, ***W***, and ***Sn-W*** mineralization are characteristic. ***Ta-Nb-Be*** and ***Li-Cs*** specialization is almost absent.

Currently, the primary sources of ***Ta***, ***Nb***, ***Be***, ***Li***, and ***Cs*** are granite pegmatites. Greisen and quartz-vein objects are smaller in scale, while known cassiterite, scheelite, and tantalum-niobate placers have been largely worked out and are not considered in this study.

The formation types of rare-metal granitoids of the Kalba-Narym Belt, according to [6, 9], are summarized below.

Results and Discussion

Exploration criteria and indicators

They have been studied and summarized in numerous works since the 1950s. Based on the data of [2, 3, 5, 6, et al.], these criteria can be systematized as follows:

Magmatic criteria. The granitoids of the Kalba Complex are ore-forming for most rare-metal objects of the Kalba-Narym Belt. At the same time, the leucogranites of the Monastyr Complex are less significant in this regard. The most recent derivatives, the dikes of the Mirolyubovsky complex, are practically uncomplicated.

Major rare-metal pegmatite deposits are associated with Phase I granites of the Kalba Complex. The main criteria for ore-bearing potential [2, 7] include: extensive areal development; weakly expressed post-magmatic alterations (mainly microclinization); lack of uniformity in facies composition (granites, granodiorites, plagiogranites, etc.) with plagioclase predominating over K-feldspar; enrichment in rare alkalis (***Li*** + ***Rb*** + ***Cs***), whose sum is twice that of Phase II granites; geochemical specialization in rare elements (***Ta***, ***Nb***, ***Be***, ***Li***, ***Sn***), fixed in rock-forming minerals – quartz, feldspars, and biotite; and spatial association of vein rocks with rare-metal pegmatites.

Phase II granites are characterized by local processes of albitization and greisenization, accompanied by their own rare-metal pegmatite deposits, with major ore minerals being tantalite and beryl. Phase II granites are also associated with albitite-greisen (apogranite) type occurrences with tin-tantalum-lithium mineralization (Karasu, Novo-Akhmirovskoe, Apogranitnoye). Small-scale greisen-quartz vein and hydrothermal ***Sn-W*** occurrences are also known (Kozlovskoe, Karash, Burabay, etc.).

Leucocratic granites of the Monastyr Complex (P_{1-2}) are represented by large granite massifs in the Narym District and form small tabular bodies in marginal endocontacts of the Mirolyubov, Kaindin, and Karatsaygan massifs. They are specialized in rare elements (***Ta***, ***Li***, ***W***, ***Sn***, ***REE***), but due to crystal-chemical dispersion, they are not associated with rare-metal objects; only chamber-type crystal-bearing occurrences (Dun-

Table 1

Formation types of rare-metal granitoids of the Kalba-Narym Belt and associated deposits

Кесте 1

Қалба-Нарым белдеуінің сирекметалды гранитоидтарының формациялық түрлері және оларға байланысты кен орындары

Таблица 1

Формационные типы редкометальных гранитоидов Калба-Нарымского пояса и связанных с ними месторождений

Formation	Petrographic characteristics	Mineralization	Objects
Kalba Complex (P_1),			
Granodiorite subformation	Normal ***K-Na*** series, moderate basicity, highly aluminous, with garnet-ilmenite-apatite accessory specialization	Rare-metal pegmatitic (***Ta***, ***Nb***, ***Be***, ***Li***, ***Cs***, ***Sn***)	Bakennoe, Yubileinoe, Belaya Gora
		Blocky microcline pegmatites (***Nb***, ***Be***, microcline, quartz)	Nizhniy Laibulak
		Quartz-vein type (***Sn***, ***W***)	Chudskoe, Kaindinskoe, Cherdoyak
Granite subformation	Normal ***K-Na*** series, low basicity, highly aluminous, with ilmenite-apatite accessory specialization	Lithium-tantalum pegmatitic (***Ta***, ***Li***, ***Nb***, ***Be***)	Kvartsevoye Akhmetkino
		Albitite-greisen type (apogranites, ***Sn***, ***Ta***, ***Li***)	Karasu, Novo-Akhmirovskoe, Muncha
		Greisen/quartz-vein type (***Sn***, ***W***)	Karash, Kozlovskoe
Monastyr Complex ($P_2 – T_1$),			
Granite subformation	Subalkaline ***K–N***a series, high-pyrometamorphic, highly aluminous, with ilmenite-fluorite-monazite accessory specialization	Chamber-type crystal-bearing pegmatites (non-ore minerals) and mineralization zones with monazite	Zhamantas, Dungalinskoe, Karagayly
Leucogranite subformation	Leucocratic granites, vein-type granites, aplites, and quartz veins	Quartz-vein type (***Sn***, ***W***)	Bolshevik, Razdolnenskoe

galinskoe) and small hydrothermal tungsten occurrences in the Mirolyubov massif (Bolshevik, Razdolnenskoe, Vostochnoye, etc.) are known.

Mineralogical-geochemical criteria. Geochemical studies highlight alkali-deficient and ore-specific element spectra (***Li***, ***Rb***, ***Cs***, ***Ta***, ***Nb***, ***Be***, ***Sn***) in granites, ores, and monomineralic fractions of feldspars, quartz, and micas [7]. This indicates a similar composition of the parent magmatic melts and pegmatite-forming fluids, emphasizing the synchronicity of granite crystallization and pegmatite formation.

There are four consecutive stages: microclinization, accompanied by the formation of blocky microcline pegmatites. Indicators include blocks of microcline and quartz, nests of large-platy muscovite containing ***Ta***, ***Nb***, ***Be***, ***Li***, and other elements. Ore minerals include platy columbite and prismatic beryl crystals.

Albitization is associated with the formation of albite-microcline and albitite complexes, which constitute the matrix of rare-metal pegmatite veins. Dominant typomorphic minerals are albite, muscovite, green tourmaline, pink garnet, fluorapatite, and phosphate minerals.

Greisenization, observed in quartz-albite-muscovite complexes formed in the interiors of pegmatite veins. Typomorphic minerals are green muscovite, fluorapatite, green tourmaline, tantalite-columbite, and cassiterite. A notable feature is extremely high Ta content (up to 1% and above) and ***Sn*** enrichment.

Spodumene formation, occurring at the late stage of the pegmatite process, is characterized by massive accumulations, discrete nests, and large crystals of spodumene. The resulting quartz-cleavelandite and spodumene-quartz complexes are the most productive. Other indicators include cleavelandite, spodumene, amblygonite, pollucite, lepidolite, colored tourmalines, fluorite, and tantalum-bearing minerals (manganotantalite, microlite, ixiolite), among others.

The most productive pegmatite veins are those exhibiting all four metasomatic stages intensively.

Structural-tectonic criteria. The association of rare-metal objects of the Kalba-Narym Belt with vein systems has been recognized since the 1950s. The largest pegmatite fields – Asubulak, Belogorsko-Baymurzino, Chernovin, Karagoin-Lukon, etc. – occur in endo- and exocontact zones of granite massifs, in roof sag areas and residual blocks, where they are localized in tectonically weakened zones flanking second- and third-order faults. As an example, a diagram illustrates the increased density of vein rocks per unit area in relation to fault tectonics and the localization of rare-metal occurrences in the Central District of the Kalba-Narym Belt. A positive correlation is evident between zones of high vein density (% of total area) and the presence of rare-metal occurrences.

The most important factor in the localization of ore veins is multi-level granite massif architecture, represented by alternating tabular granite layers and platy xenoliths of host rocks. Such formations are noted at intersections of massifs by first- and second-order faults and are most often associated with complicating third- and fourth-order fracture systems. Host rocks act as screens and lithological traps beneath which complexes of pegmatite bodies are localized, with the vein fields themselves acquiring a tiered structure. Xenoliths are most composed of Middle-Upper Devonian flysch-type formations, represented by carbonaceous shales and sandstones. Promising locations also include sag zones of granite roofs, where ore-forming fluids were trapped by previously formed sedimentary layers.

Thus, vein-hosted rocks, 95% of which belong to Phase III of the Kalba Complex, are concentrated in fields and zones. The most favorable sites for pegmatite formation and localization are areas of tiered massif structures, where granitoids actively interact with host rocks.

Based on the formation characteristics described above and the set of exploration criteria and indicators, the prospects of the Kalba-Narym Belt for rare-metal resources can be outlined as follows:

- Due to the long-term study of the Kalba-Narym Belt, geological exploration and mining activities, the discovery of new economically attractive objects across most of the ore-bearing formations is unlikely, except in poorly studied areas covered by Cenozoic unconsolidated deposits. The discovery of new pegmatite and albitite-greisen occurrences not exposed at the surface is also possible.

- Areas covered by thick sequences of unconsolidated deposits are of interest, particularly most of the Shulbinsky District. Geophysical work in 1990–2000 revealed a wide development of granitoid massifs with contact metasomatosis of the host sedimentary rocks within the southern part of sheet M-44-IX and the northern part of M-44-XV [2, 7]. Several manifestations of ***Sn-W*** *mineralization were found (Kozhankul, Korosteli, Stepanovskoye).*

- The Karagoin-Saryozek ore zone of Central Kalba shows promise for new discoveries. Here, sagging of the massif roofs is characteristic: granites outcrop at the periphery, while central locations are covered by Takyr Series shales. Of particular interest are albite–spodumene pegmatites associated with Kunush plagiogranites and dykes (deposits and occurrences at Akhmetkino, Tochka, Novo-Saryozek, Kushbarlyk, Medvedka), featuring low ***Ta***, ***Be***, ***Sn*** *content but large estimated lithium resources.*

- Non-pegmatitic rare-metal mineralization includes albitite–greisen occurrences with ***Sn-Ta-Li*** *mineralization (Novo-Akhmirovskoe, Karasu, Malo-Chernovinskoe, Apogranitnoye, Tortkalmak, etc.). In terms of formation characteristics, these are comparable to the Sarymbet deposit (Northern Kazakhstan) and Alakha (Altai Mountains), remain poorly studied, and have significant potential for lithium, tantalum, zirconium, and rare-earth elements.*

Taking into account the tasks set in research project PCF BR27100483, machine learning methods are used in the form of a set of quantitative data analysis methods based on the construction of models that identify the relationship between a set of features and the target function. Unlike expert systems based on predefined rules, machine learning methods generate models based on empirical data, identifying statistical dependencies without explicitly programming decision-making rules.

The algorithm identifies patterns in the input data, establishing correlations, for example, between geochemical composition and rock type. Based on these relationships, the system then determines dependencies between geochemical indicators and rock types. However, most machine learning algorithms are empirical and do not reflect the primary causes of observed phenomena. In other words, forecasts produced using machine learning tools are not free from errors, particularly if the model is not validated by domain experts [11, 12].

In this study, data preparation for rare-metal objects of the Kalba-Narym Belt utilized 28 specialized reports covering various stages of exploration, 15 published monographs, PhD theses and articles, large-scale geological maps, factual material maps, sections, and sampling schemes from deposits including Karagoin, Medvedka, Tochka, Akhmetkino, Targynskoe, Yubileinoe, and Krasny Kordon.

A total of 280 occurrences, deposits, and mineralization points were included in a database with parameters such as: object name, XY coordinates, elevation marks, formation-morphological parameters, concentrations of useful components, and resource/reserve data. Formation-morphological parameters were organized into a tree-like hierarchical structure generally corresponding to: «formation group – host formation – ore-bearing formation – ore body morphology – mineral associations – ore mineralization – ore elements, satellites, and accessories».

The database of 280 rare-metal mineralization objects was overlaid on the geological base map and complemented by consolidated results of regional geophysics – magnetic and gravity field maps. Landsat imagery and Sentinel-2 spectral zone data were also widely used. Using these datasets together with a digital elevation model enables automation of morphostructural mapping, particularly of lineaments and circular structures. Faults identified through morphostructural analysis, especially 3rd–4th order faults flanking main fractures and compression zones, often correlate with rare-metal occurrences.

Conclusion

Thus, data preparation for artificial intelligence applications under project BR 27100483 involves creating a point database of known objects while integrating raster or vector geophysical data and remote sensing materials in various spectral ranges. Combining these datasets in established AI algorithms supports achieving the objectives of the grant.

In conclusion, there is a certain euphoria in recent years regarding the widely publicized use of machine learning methods, including for resource evaluation, forecasting, and exploration. Clearly, the use of AI technologies in geology is still at an early stage, as discussed above. Nevertheless, large-scale digitization of archival materials, combined with the development and adaptation of machine learning algorithms for specific exploration and forecasting tasks, promises to significantly advance AI applications in geology.

The implementation of the research project BR 27100483, of which this report represents an intermediate stage, will provide experience in preparing and utilizing extensive factual materials accumulated in geological archives. This will enable higher-level conclusions and syntheses aimed both at strengthening the mineral resource base of the Republic of Kazakhstan and supporting the successful operations of private companies.

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