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«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

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Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

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GEOLOGICAL STRUCTURE, MATERIAL COMPOSITION OF SKARNS, ORE-FORMING STAGES OF THE KARAULKEN IRON ORE DEPOSIT (CENTRAL KAZAKHSTAN)

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Abstract. *Relevance.* Iron-skarn deposits of Central Kazakhstan are important sources of iron ore and strategic raw materials for the mining industry. The northwestern Balkhash region contains promising skarn systems characterized by complex mineralogical and structural features controlling ore localization and beneficiation properties. However, many aspects of the geological structure, mineral composition, and stages of ore formation of the Karaulken deposit remain insufficiently studied. *Objective.* To investigate the geological structure, mineral composition, textural–structural characteristics, and ore-forming stages of the Karaulken iron-skarn deposit using an integrated geological and mineralogical approach. *Methods.* The study included field investigations, petrographic and mineralogical analyses, X-ray fluorescence analysis, interpretation of magnetic survey data, optical and electron microscopy, and geochemical analyses of drill-core samples. A total of 235 representative core samples obtained from three drill holes were examined to determine mineral associations, geochemical variations, and ore localization features. *Results.* Ore mineralization is localized within exoskarn and endoskarn zones controlled by strike-slip and thrust-related fault systems of the Akbastau zone. The skarns are predominantly composed of garnet–pyroxene–epidote assemblages with magnetite as the principal ore mineral accompanied by hematite and pyrite. Several mineral associations reflecting progressive and retrogressive metasomatic stages were identified. Geochemical analyses revealed variations in Fe_2O_3, SiO_2, and CaO contents corresponding to silicate, calcium-rich, and magnetite skarn facies. Massive, disseminated, veinlet, and schistose ore textures significantly influence beneficiation characteristics. A probable multistage evolution model of the Karaulken skarn system was established, including contact metamorphic, prograde skarn, retrograde hydrothermal–metasomatic, and supergene oxidation stages. *Conclusions.* The Karaulken deposit represents a typical Late Paleozoic contact–metasomatic iron-skarn system formed within the contact zone between Devonian carbonate–siliceous sequences and granitoid intrusions. The obtained results improve understanding of iron-skarn systems in Central Kazakhstan and may be applied in metallogenic forecasting and optimization of ore beneficiation technologies.

Keywords: iron skarns, exoskarns and endoskarns, garnet–pyroxene–epidote association, magnetite ores, mineralogical and petrographic composition of skarns, texture and structure of ore-hosting rocks, Central Kazakhstan

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ҚАРАӨЛКЕН ТЕМІР КЕН ОРНЫНЫҢ (ОРТАЛЫҚ ҚАЗАҚСТАН) ГЕОЛОГИЯЛЫҚ ҚҰРЫЛЫСЫ, СКАРНДАРДЫҢ МИНЕРАЛДЫҚ ҚҰРАМЫ ЖӘНЕ КЕН ТҮЗІЛУ САТЫЛАРЫ

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Аннотация. *Өзектілігі.* Орталық Қазақстандағы темір-скарн кен орындары темір кені мен стратегиялық минералдық шикізаттың маңызды көздерінің бірі болып табылады. Солтүстік-Батыс Балқаш аймағында кенденудің локализациясы мен рудаларды байыту қасиеттерін анықтайтын күрделі минералогиялық және құрылымдық ерекшеліктерге ие перспективалы скарн жүйелері таралған. Алайда Қараөлкен кен орнының геологиялық құрылысы, минералдық құрамы және кен түзілу сатыларына қатысты көптеген мәселелер әлі де жеткілікті деңгейде зерттелмеген. *Мақсаты.* Қараөлкен темір-скарн кен орнының геологиялық құрылысын, минералдық құрамын, текстуралық-құрылымдық ерекшеліктерін және кен түзілу сатыларын кешенді геологиялық-минералогиялық тәсіл негізінде зерттеу. *Әдістері.* Зерттеу барысында далалық геологиялық жұмыстар, петрографиялық және минералогиялық талдаулар, рентгенфлуоресценттік талдау, магниттік түсірілім деректерін интерпретациялау, оптикалық және электрондық микроскопия, сондай-ақ бұрғылау керндерінің геохимиялық талдаулары жүргізілді. Үш бұрғылау ұңғымасынан алынған 235 репрезентативті керн үлгісі минералдық ассоциацияларды, геохимиялық өзгерістерді және кенденудің таралу ерекшеліктерін анықтау мақсатында зерттелді. *Нәтижелері.* Рудалы минералдану Ақбастау аймағының ығыспалы және жапсарлы жарылымдарымен бақыланатын экзоскарн және эндоскарн аймақтарында шоғырланған. Скарндар негізінен гранат-пироксен-эпидотты ассоциациялардан тұрады, мұнда негізгі рудалы минерал ретінде магнетит басым дамыған, ал гематит пен пирит қосалқы минералдар ретінде кездеседі. Прогрессивті және регрессивті метасоматикалық сатыларды көрсететін бірнеше минералдық ассоциациялар анықталды. Геохимиялық талдаулар Fe_2O_3, SiO_2 және CaO құрамдарының силикатты, кальцийлі және магнетитті скарн фацияларына сәйкес өзгеретінін көрсетті. Массивті, сеппелі, желілі және сланецті текстуралар рудаларды байыту тиімділігіне айтарлықтай әсер етеді. Қараөлкен скарн жүйесінің контактылы метаморфизм, прогрессивті скарнтүзілу, регрессивті гидротермалды-метасоматикалық және гипергендік тотығу сатыларын қамтитын көпсатылы эволюциялық моделі ұсынылды.

Қорытынды. Қараөлкен кен орны девондық карбонатты-кремнийлі жыныстар мен гранитоид интрузияларының жанасу аймағында қалыптасқан кеш палеозойлық контактылы-метасоматикалық темір-скарн жүйесінің типтік үлгісі болып табылады. Алынған нәтижелер Орталық Қазақстандағы темір-скарн жүйелері туралы ғылыми түсініктерді кеңейтіп, металлогендік болжау мен рудаларды байыту технологияларын жетілдіруде қолданылуы мүмкін.

Түйін сөздер: темір-скарндар, экзоскарндар және эндоскарндар, гранат-пироксен-эпидотты ассоциация, магнетитті кендер, скарндардың минералогиялық және петрографиялық құрамы, кен сыйыстырушы жыныстардың текстурасы мен құрылымы, Орталық Қазақстан

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ГЕОЛОГИЧЕСКОЕ СТРОЕНИЕ, ВЕЩЕСТВЕННЫЙ СОСТАВ СКАРНОВ, СТАДИИ РУДООБРАЗОВАНИЯ ЖЕЛЕЗОРУДНОГО МЕСТОРОЖДЕНИЯ КАРАУЛЬКЕН (ЦЕНТРАЛЬНЫЙ КАЗАХСТАН)

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Аннотация. *Актуальность*. Железо-скарновые месторождения Центрального Казахстана являются важными источниками железных руд и стратегического минерального сырья для горнодобывающей промышленности. В северо-западном Прибалхашье распространены перспективные скарновые системы, характеризующиеся сложными минералогическими и структурными особенностями, которые контролируют локализацию оруденения и технологические свойства руд при обогащении. Однако многие аспекты геологического строения, вещественного состава и стадий рудообразования месторождения Караулькен остаются недостаточно изученными. *Цель*. Исследовать геологическое строение, минеральный состав, текстурно-структурные особенности и стадии рудообразования железо-скарнового месторождения Караулькен на основе комплексного геолого-минералогического подхода. *Методы*. В ходе исследования выполнены полевые геологические работы, петрографические и минералогические исследования, рентгенофлуоресцентный анализ, интерпретация данных магнитной съемки, оптическая и электронная микроскопия, а также геохимические анализы керновых проб. Изучены 235 репрезентативных образцов керна из трех скважин для определения минеральных ассоциаций, геохимических вариаций и закономерностей локализации оруденения. *Результаты и выводы*. Рудная минерализация локализована в пределах экзоскарновых и эндоскарновых зон, контролируемых сдвигово-надвиговыми нарушениями Акбастауской зоны. Скарны представлены преимущественно гранат-пироксен-эпидотовыми ассоциациями, где основным рудным минералом является магнетит при подчиненном развитии гематита и пирита. Выделены минеральные ассоциации, отражающие прогрессивные и регрессивные стадии метасоматизма. Геохимические исследования показали вариации содержаний Fe_2O_3, SiO_2 и CaO, соответствующие силикатным, кальциевым и магнетитовым фациям скарнов. Массивные, вкрапленные, прожилковые и сланцеватые текстуры оказывают существенное влияние на технологические свойства руд. Предложена вероятная многостадийная модель эволюции скарновой системы Караулькен, включающая стадии контактного метаморфизма, прогрессивного скарнообразования, регрессивного гидротермально-метасоматического преобразования и гипергенного окисления. Месторождение Караулькен представляет собой типичную позднепалеозойскую контактно-метасоматическую железо-скарновую систему, сформированную в зоне контакта девонских карбонатно-кремнистых толщ и гранитоидных интрузий. Полученные результаты расширяют представления о железо-скарновых системах Центрального Казахстана и могут быть использованы при металлогеническом прогнозировании и совершенствовании технологий обогащения руд.

Ключевые слова: железорудные скарны, экзо- и эндоскарны, гранат-пироксен-эпидотовая ассоциация, магнетитовые руды, минералогический и петрографический состав скарнов, текстура и структура рудовмещающих пород, Центральный Казахстан

Introduction. Iron-bearing skarns are contact–metasomatic formations developed in zones of interaction between granitoid intrusions and carbonate sequences. They are characterized by a diverse mineralogical composition dominated by magnetite, hematite, and pyrite, accompanied by various sulfide and silicate minerals. Skarn deposits in Kazakhstan represent important sources of iron ore (Shcherba, 1967; Satpayev, 1968; Bespalov, 1975; Bekmukhametov, 1987; Bekzhanov et al., 2000; Nikitchenko, 2002; Kubeeva et al., 2010; Edilbaev, 2011; Zholtayev et al., 2024).

The mineralogical and textural–structural attributes of skarns exert a decisive influence on ore quality and beneficiation efficiency (Nikitchenko, 2002; Kubeeva et al., 2010; Edilbaev, 2011; Zhukov et al., 2016; Korobkin et al., 2025). The variability of textures–such as disseminated, veinlet, and inclusion-rich types–controls the physicochemical properties of the ore and governs its technological behavior.

In the northwestern Balkhash region (Central Kazakhstan) lies a highly prospective iron-ore district composed of a series of skarn contact–metasomatic deposits and mineral occurrences, including Bapy, Zhuantobe, Karaulken, Akchagyl, Ustobe, Kiyik, Taitobe, Tomashev, Kyzyl-Sayak, Abylkhair, and Kyzylespe (Figures 1–4). Geological investigations in this region began in the early 20th century, when the first systematic traverse routes were established. In subsequent decades–most notably during the construction of the Karaganda–Balkhash railway–exploration activity intensified, and individual sites and ore bodies were examined according to their industrial potential and strategic importance (Bekmukhametov, 1987; Nikitchenko, 2002; Kubeeva et al., 2010; Edilbaev, 2011; Zhukov et al., 2016; Zholtayev et al., 2024; Korobkin et al., 2025).

Processing of iron-rich skarns employs modern methods of magnetic separation, flotation, and hydrometallurgical treatment aimed at maximizing the recovery of iron and associated elements. The efficiency of these processes is largely determined by the mineralogical mode of iron occurrence, textural–structural ore features, and the character of sulfide inclusions. Accordingly, comprehensive geological and mineralogical investigations of skarn ores from the Karaulken deposit acquire practical significance for optimizing processing flowsheets and improving the economic efficiency of beneficiation.

The northwestern Balkhash region (Bapy ore field) is regarded as a strategically important reserve iron-ore province capable of replenishing the mineral resource base of Kazakhstan's operating mining–metallurgical enterprises through the development of medium- and small-sized deposits with proven industrial potential (Kubeeva et al., 2010; Edilbaev, 2011; Zhukov et al., 2016; Korobkin et al., 2025).

Analysis of previously conducted studies on iron-skarn mineralization within the region, including the Karaulken deposit, has shown that a number of issues remain insufficiently investigated using modern structural, mineralogical, and geochemical methods. This particularly concerns the genesis of mineralization, the stages of skarn system formation, and the technological properties of the ores. The present study provides new mineralogical, petrographic, and geochemical data that refine the formation model of the Karaulken skarn system and allow a more detailed comparison with other iron-skarn deposits of the northwestern Balkhash region.

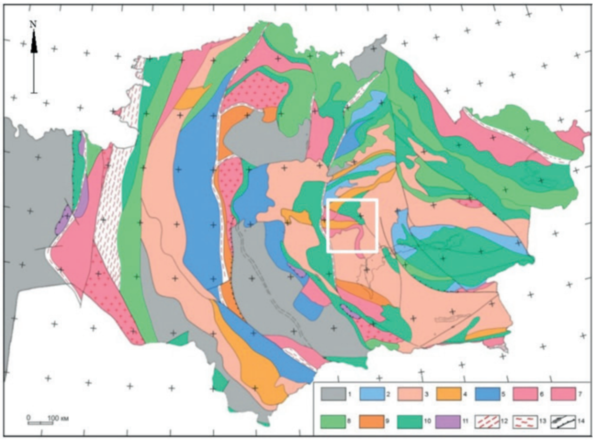

Figure 1. Tectonic zoning scheme of the Paleozoic regions of Kazakhstan (Korobkin and Buslov, 2011; Korobkin et al., 2025) (the iron ore district of the northwestern Balkhash region is highlighted by a white rectangle). 1 – tectonic depressions (sedimentary basins); 2 – fragments of fore-arc terraces; 3 – volcanic and volcano-plutonic belts; 4 – rifts; 5 – zones of fold–thrust and strike-slip deformation; 6,7 – cratonic terranes (6 – weakly granitized, 7 – with granite–gneiss domes); 8 – fragments of volcanic island arcs; 9 – fragments of rift-related basins; 10 – collisional sutures; 11 – ophiolitic allochthons; 12 – transform suture and shear zones; 13 – schist zones; 14 – post-collisional faults: (a) strike-slip, (b) thrust.

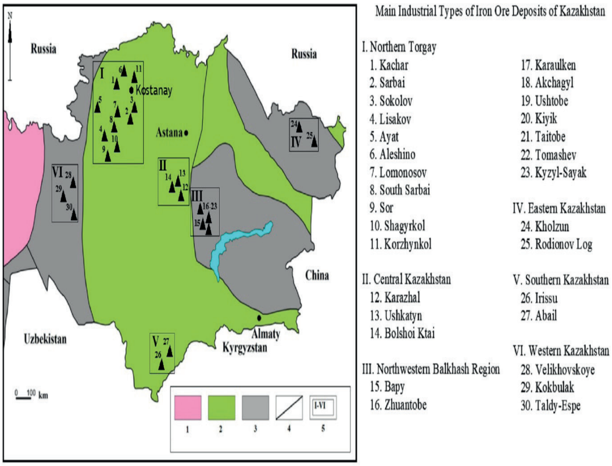

Figure 2. Schematic map of the main tectonic units and distribution of the principal industrial types of iron ore deposits in Kazakhstan (Zhukov et al., 2016; Korobkin et al., 2025): (1) East European Craton; (2, 3) Kazakh segment of the Central Asian Fold Belt (2 – Caledonian, 3 – Hercynian fold systems); (4) geological boundaries; (5) outlines of iron ore districts. Main iron ore deposits of Kazakhstan: I – Northern Torgai: 1 – Kachar, 2 – Sarybai, 3 – Sokolov, 4 – Lisakov, 5 – Ayatsk, 6 – Alyoshino, 7 – Lomonosov, 8 – South Sarybai, 9 – Sor, 10 – Shagyrcol, 11 – Korzhinkol; II – Central Kazakhstan: 12 – Karazhal, 13 – Ushkatyn, 14 – Bolshoy Ktai; III – Northwestern Balkhash region: 15 – Bapy, 16 – Zhuantobe; 17 – Karaulken, 18 – Akchagyl, 19 – Ushtobe, 20 – Kiyik, 21 – Taitobe, 22 – Tomashev, 23 – Kyzyl-Sayak, IV – Eastern Kazakhstan: 24 – Kholzun, 25 – Rodionov Log; V – Southern Kazakhstan: 26 – Irissu, 27 – Abail; VI – Western Kazakhstan: 28 – Velikhov, 29 – Kokbulak, 30 – Taldy-Espe.

Geological setting. Kazakhstan is one of the global leaders in iron-ore endowment, ranking eighth worldwide in terms of explored reserves (Zhukov et al., 2016; Zholtayev et al., 2024). Six major iron-ore provinces are distinguished within its territory: (I) North Torgai, (II) Atasu, (III) Northwestern Balkhash, (IV) East Kazakhstan, (V) South Kazakhstan, and (VI) West Kazakhstan. Each province is characterized by its own set of geological–industrial and genetic types of ore deposits, reflecting the complex tectono-magmatic evolution of the region (Figure 3).

In Central Kazakhstan, two key iron-ore districts are recognized–the Atasau district and the Northwestern Balkhash district (Figure 3). The Atasu zone hosts several large iron–manganese deposits, including Karazhal, Ushkatyn III, and Kentobe, with combined reserves exceeding 300 Mt of high-grade ore. The Northwestern Balkhash district is considered a reserve territory and is characterized by medium- and small-scale skarn-type deposits that possess significant industrial potential.

The Karaulken deposit is located in the northwestern Balkhash region, along the eastern margin of the Betpakdala Desert (Central Kazakhstan) (Figures 3–5). It forms part of a complex metallogenic system associated with the Akbastau fault zone and the Kyzyl-Sayak group of skarn deposits. The geological structure of Karaulken has been extensively examined through field mapping, geophysical surveys, and mineralogical–petrographic investigations, which have substantially refined current understanding of the formation patterns of skarn-type iron-ore systems in Central Kazakhstan (Boyko et al., 2019; Korobkin et al., 2025).

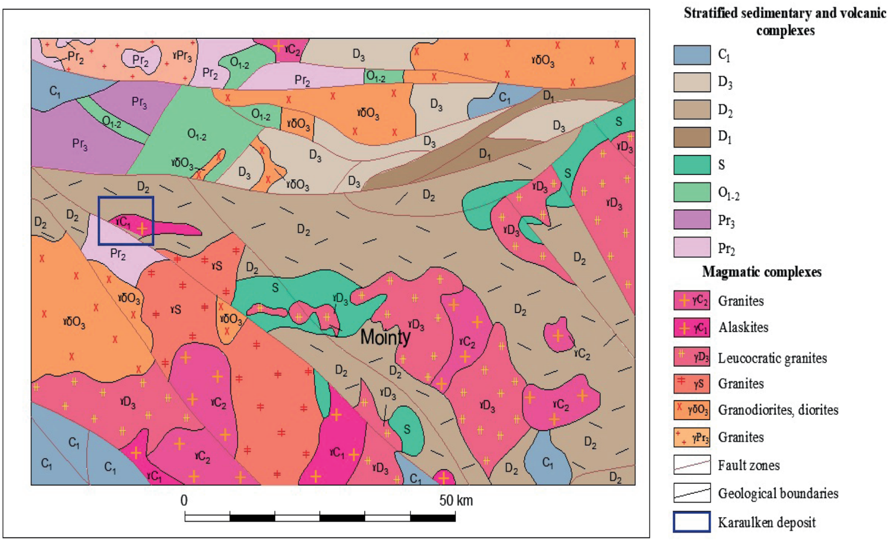

Figure 3. Geological map of the Karaulken deposit compiled by the authors based on data obtained during field investigations.

Materials and methods. A comprehensive analytical program was implemented to investigate the geological, mineralogical, and geochemical characteristics of the Karaulken iron-skarn deposit. This workflow included field studies, mineralogical and petrographic analyses, and multielement chemical testing. Such an integrated approach made it possible to identify the textural–structural and compositional features of the host rocks, determine mineral associations, and reconstruct the stages of skarn formation.

Core material was obtained from three drill holes (W-1 – W-3) completed within the main ore-bearing zone of the Karaulken deposit. Sampling was carried out with respect to lithological boundaries and mineralogical variations in the host rocks. A total of 235 representative core samples were collected, with individual sample lengths ranging from 0.15 to 2.7 m (average 1.7 m).

Thin sections were examined under transmitted light using LEICA DM750 (Leica Mikrosysteme Vertrieb GmbH, Wetzlar, Germany) and POLAM R-312 (LOMO-Mikroanalysis LLC, Saint Petersburg, Russia) polarizing microscopes. Polished sections (ore mounts) were studied using a LEICA DMi8 inverted microscope (Leica Mikrosysteme Vertrieb GmbH, Wetzlar, Germany). These observations enabled a detailed characterization of mineral assemblages, relationships between ore and rock-forming minerals, and the identification of replacement textures, zoning, and recrystallization features typical of multistage skarn systems.

Additional information on ore morphology and microtextures was obtained by electron microscopy. Analyses were performed using an INCA 8N8RGY energy-dispersive spectrometer (Oxford Instruments, Abingdon, UK) at 25 kV accelerating voltage and 25 mA beam current. Imaging in backscattered electrons allowed the recognition of fine structural features and mineral intergrowths indicative of repeated stages of fluid–metasomatic activity.

The chemical composition of samples was determined by X-ray fluorescence analysis (XRF) using a SPECTRO XEPOS III spectrometer (SPECTRO Analytical Instruments GmbH, Kleve, Germany). Samples were prepared as pressed powder pellets with boric acid as a binder, and, when necessary, as fused glass beads to improve sample homogeneity. Analytical precision and reproducibility were monitored using certified reference materials and repeat measurements.

Each sample was analyzed twice; the arithmetic mean of the two measurements was used, with the difference between them not exceeding the established repeatability threshold. The analytical program included the determination of total iron (reported as Fe_2O_3) and a semiquantitative multielement analysis for 46 components.

Analytical data processing was performed using dedicated software supplied with the instrumentation. The reliability of results was checked through internal standards and statistical evaluation of duplicates. Average concentrations of major oxides and trace elements for each drill hole are presented in Table 1.

Interpretation of magnetic survey results obtained within the Karaulken deposit during previous exploration works made it possible to delineate ore-bearing zones (Boyko et al., 2019). Positive magnetic anomalies correspond to magnetiterich exoskarn and endoskarn zones and reflect the structural localization of mineralization. The interpretation of magnetic data was integrated with geological mapping, drill-core logging, and mineralogical–petrographic observations.

The combined use of optical microscopy, electron microscopy, and geochemical methods enabled a consistent link to be established between the mineralogical and textural features of the ores and their chemical composition, forming a basis for reconstructing the conditions and stages of skarn formation at the Karaulken deposit.

Results. *Geological Characteristics of the Deposit.* The deposit is situated within the Akbastau fault zone, which forms part of the Central Kazakhstan Fold Belt. At the regional scale, Karaulken belongs to the Atar syncline–a major northeast-trending structure composed predominantly of Devonian sedimentary–volcanogenic sequences (Figures 4–7).

The area is characterized by the superposition of several tectonic deformation stages. The earliest northeast-trending fold structures are overprinted by sublatitudinal and meridional faults, along which zones of silicification, skarnification, and metasomatism are concentrated. The Akbastau fault represents the principal ore-controlling structural element; the ore bodies of Karaulken are localized along its shear zone.

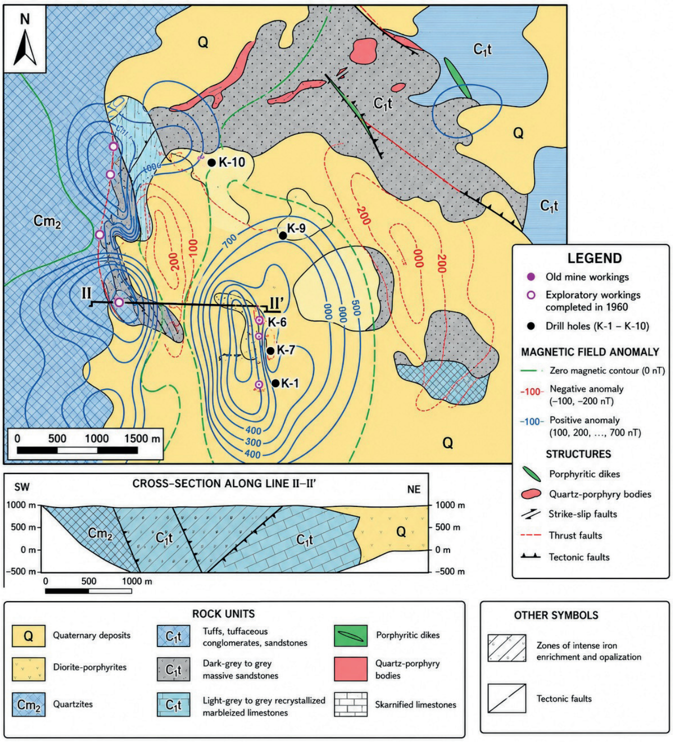

Figure 4. Geological map of the Karaulken deposit, compiled by the authors based on data obtained during fieldwork using data from (Boyko et al., 2019).

The geological structure of the deposit includes Devonian-age rocks–sandstones, siltstones, siliceous and carbonate schists, limestones, and dolomites. These strata are intruded by dikes of diorites and diorite-porphyrites, which are closely associated with the development of hydrothermal–metasomatic processes. The contact zones between carbonates and acidic magmatism are characterized by skarn formations composed of garnet, pyroxene, epidote, and magnetite. As a result of contact–metasomatic processes, the carbonate rocks have been transformed into marbles, while the siliceous rocks underwent intense silicification.

Based on the combination of geological, mineralogical, and geochemical characteristics, the mineralization is of contact–metasomatic (skarn) genesis. It is associated with the intrusion of dioritic bodies into the Devonian carbonate–siliceous strata.

The formation of ore bodies occurred through the interaction of iron-rich metasomatic fluids with limestones and dolomites in zones of tectonic faults. Late weathering processes led to the replacement of magnetite by hematite and limonite. The geological age of the mineralization is estimated as Late Devonian–Carboniferous.

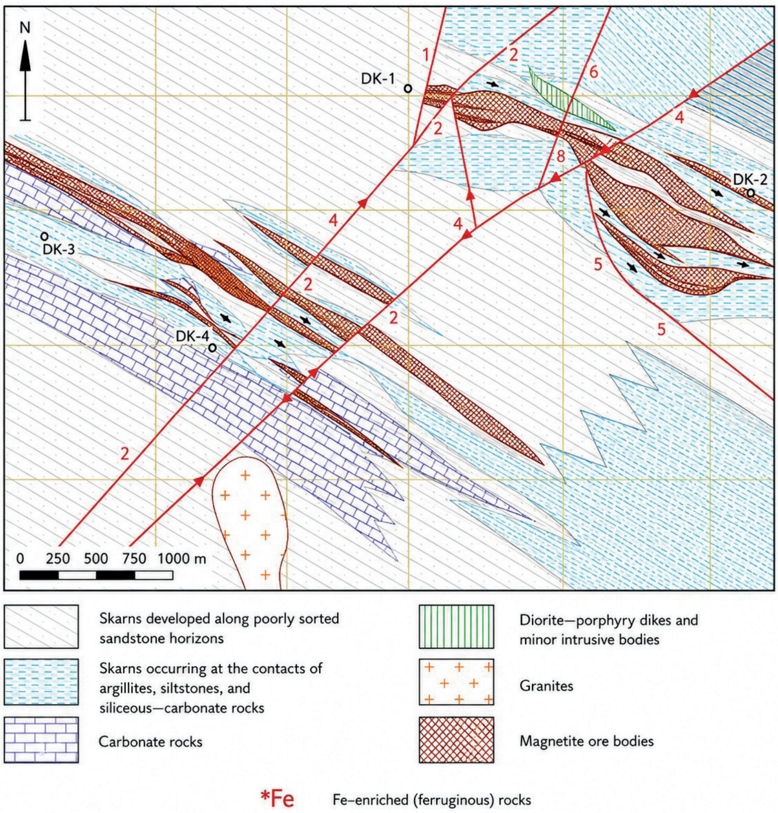

Figure 5. Geological structure of the Karaulken deposit.

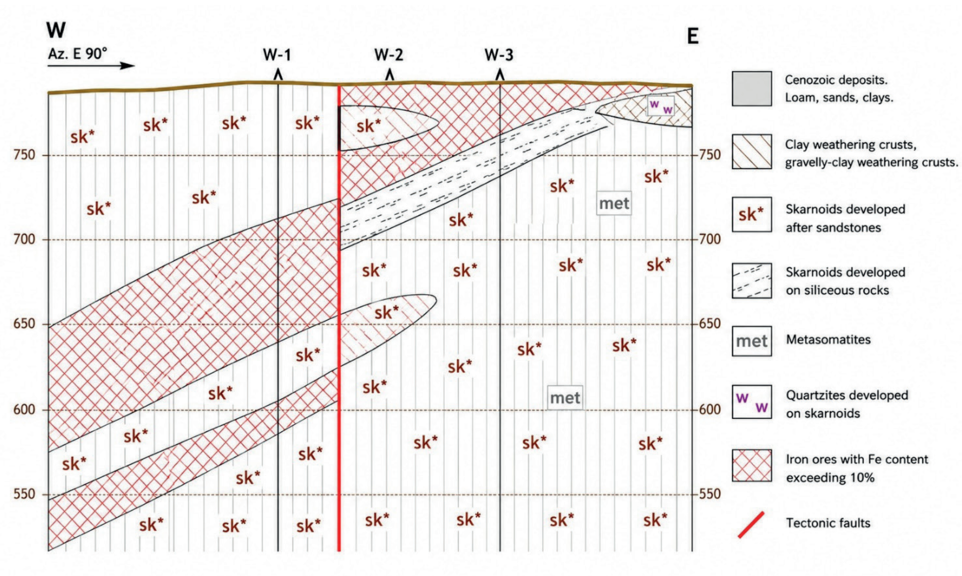

Figure 6. Detailed geological cross-section of the Karaulken deposit along profile II–II. Compiled by the authors based on field investigations and mine-workings documentation, using data from (Boyko et al., 2019).

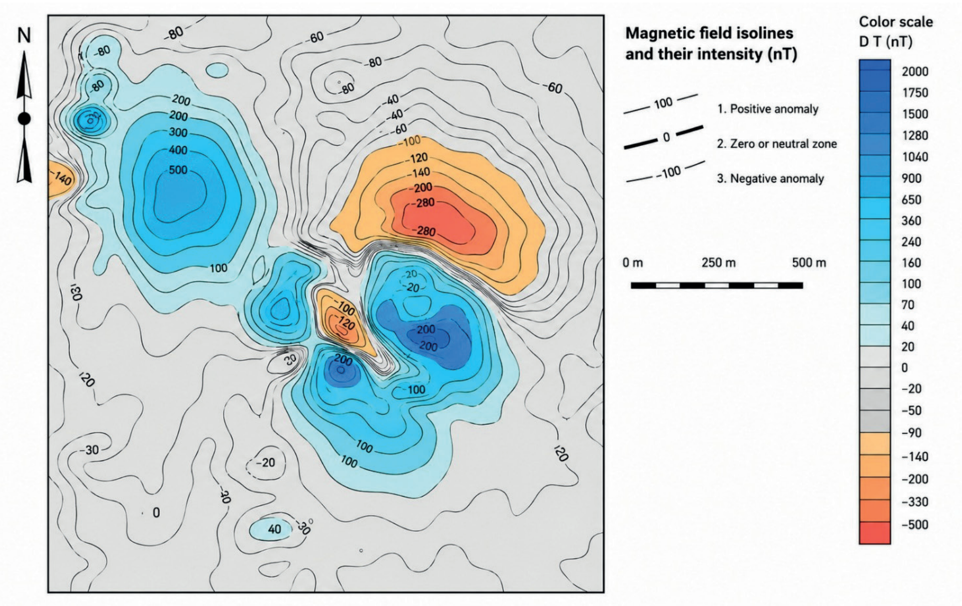

Figure 7. Magnetic field map of the Karaulken deposit. Positive anomalies correspond to skarn ore-bearing zones. The map is based on field survey results and supplemented by geophysical data from (Boyko et al., 2019).

The ore bodies occur predominantly as lens-shaped, subtabular zones localized along the contacts between marbleized limestones and siliceous–carbonate rocks. Their strike is sublatitudinal, and they dip mainly southward at angles of 30–45°. The ore bodies extend 50–300 m along strike (average 150 m), have down-dip continuity of 20–50 m (average 35 m), and range in thickness from 2 to 76 m (average 17 m). A total of 40 ore bodies have been identified. Near-surface zones have undergone minor oxidation, resulting in the formation of brown iron ores of limonite–hematite composition.

Mineral composition of the skarns. The principal ore mineral is magnetite, occurring as massive, disseminated, and veinlet aggregates. Magnetite content in the ore ranges from 10 to 100%. Subordinate ore minerals include hematite and pyrite; chalcopyrite is recorded as a rare accessory phase. Hematite forms veinlets and disseminations in near-surface horizons and is commonly associated with oxidation zones.

The gangue minerals are represented by quartz, calcite, muscovite, epidote, and iron hydroxides. Numerous microscopic observations show that magnetite frequently forms disseminations within garnet–pyroxene skarns or occurs in quartz–carbonate veinlets (Figure 8).

A) Crystalline marble, composed mainly of equigranular calcite crystals (85–95%) with dispersed grains of diopside, epidote, biotite (5–10%), magnetite, and pyrite. The rock has a characteristic saccharoidal texture formed during the prograde stage of contact metamorphism at the contact with the diorite stock. Grains of diopside and aggregates of epidote occur as small inclusions within the recrystallized carbonate matrix, locally concentrating along microfractures. This type of marble occurs in the exoskarn zone surrounding the diorite dikes and represents an early stage of metamorphic transformation preceding the development of intense subsequent metasomatic processes and the formation of magnetite ore bodies.

B) Amphibolite, composed mainly of hornblende (60–75%) and plagioclase (20–30%), with subordinate epidote, quartz, and magnetite. The rock structure varies from fine- to medium-grained; the texture is nematoblastic, schistose due to the preferred orientation of prismatic amphibole crystals. The mineral paragenesis corresponds to the amphibolite facies of metamorphism (550–650 °C, 4–6 kbar) (Korobkin et al., 2025), associated with thermal effects of the diorite intrusion. The rock is crosscut by thin quartz–epidote–calcite veinlets and contains dispersed magnetite grains, reflecting the transition to an early stage of skarn formation.

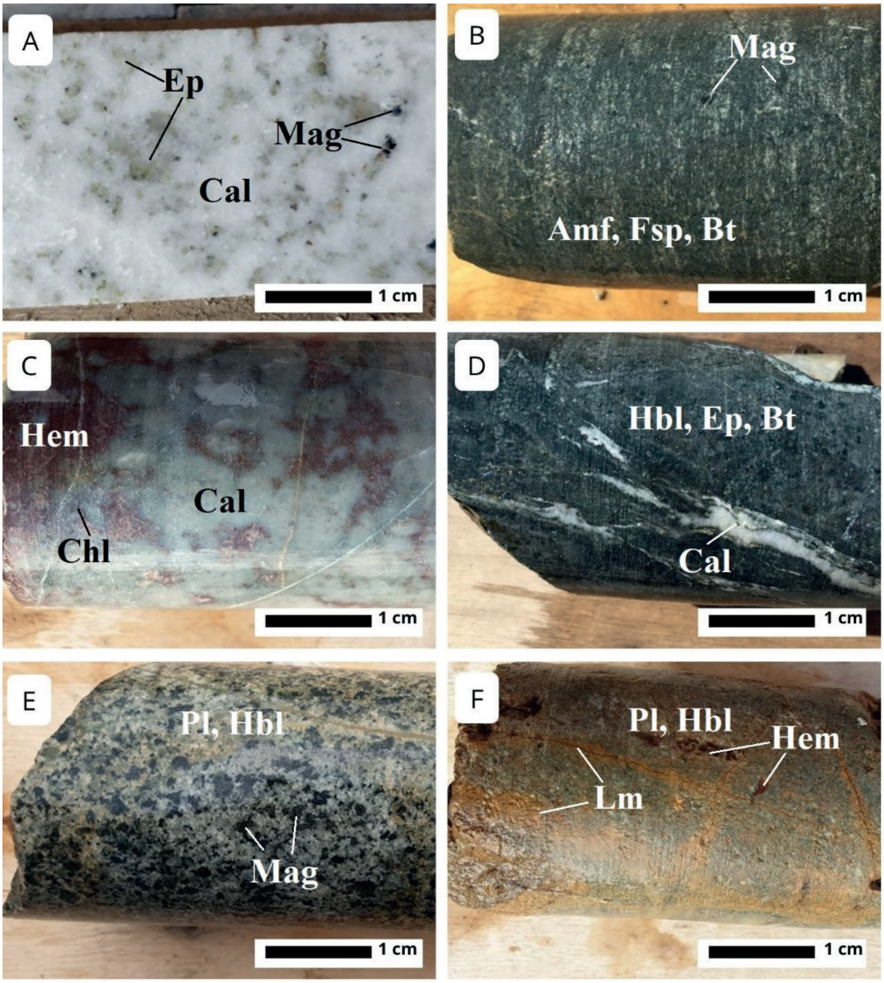

Figure 8. Representative rock types of the Karaulken iron-skarn system (Central Kazakhstan). (A) Saccharoidal calcite marble with disseminated diopside–epidote grains from the contact zone; (B) Amphibolite from the prograde metamorphic zone; (C) Epidote–calcite skarn from the retrograde hydrothermal; (D) Actinolite–quartz–chlorite skarnoid from the transitional zone between prograde and retrograde stages; (E) Diorite from the intrusive complex; (F) Limonite–hematite skarnoid from the oxidation zone. Conventional indices of minerals (Whitney and Evans, 2010): epidote group minerals (Ep); magnetite (Mag); calcite (Cal); amphibole (Amp); feldspar (Fsp); biotite (Bt); hematite (Hem); chlorite (Chl); hornblend (Hbl); plagioclase (Pl); limonite (Lm).

C) Epidote–calcite skarn from the retrograde hydrothermal zone. The rock is composed mainly of epidote (40–60%) and calcite (20–30%), with subordinate magnetite, hematite, quartz, and pyrite. The texture is spotted and veined, with characteristic brownish-red oxidation spots where magnetite has altered to hematite. Replacement of magnetite by epidote and calcite indicates decreasing temperature and increasing fluid activity during the late stages of the metasomatic process.

D) Actinolite–quartz–chlorite skarnoid from the transitional zone between prograde and retrograde stages. The rock is represented by a dark green, dense mass with veins of white quartz and calcite. The mineral composition includes actinolite (50–60%), quartz (20–30%), chlorite (10–15%), with subordinate carbonates and dispersed sulfides. This assemblage reflects a transitional retrograde hydrothermal–metasomatic stage inferred from mineral replacement relationships in which cooling fluids partially recrystallized earlier amphibolite rocks. Replacement of amphibole by chlorite and the formation of quartz veinlets indicate the onset of retrograde metasomatism and the redistribution of fluids along contact zones.

E) Diorites have a medium-grained texture and are composed mainly of plagioclase (50–60%), amphibole (20–25%), biotite (5–10%), with subordinate pyroxene and magnetite. Accessory minerals include titanite, apatite, and zircon. The diorites have undergone hydrothermal alteration, including chloritization and epidotization.

F) Skarnoid from the oxidation zone, with a mineral composition dominated by hematite and limonite (40–60%), epidote, chlorite, and calcite (20–30%), as well as residual magnetite (5–10%). Iron and manganese hydroxides and clay minerals occur in fractures and porous zones. Replacement of magnetite by hematite and limonite indicates the transition from hypogene to supergene conditions of ore formation in the Karaulken system.

Chemical composition and technological characteristics. Spectral analysis was carried out on 97 representative samples collected from drill holes W-1, W-2, and W-3. A total of 46 elements and oxides were determined using instrumental emission spectroscopy. The obtained data allow for a quantitative assessment of the composition of major and trace components that control the mineral and geochemical zonation within the skarn sequence. The concentrations of major oxides show a wide range of variations, reflecting the transition from silicate to calcic skarns and the varying intensity of iron metasomatism (Table 1).

Table 1. Key results of spectral analysis of major oxides.

Parameter	SiO_2	Al_2O_3	CaO	Fe_2O_3
Average, wt.%	51.1	17.2	12.0	6.5
Min.–Max.	1.25 – 93.3	0.01 – 32.8	0.15 – 39.1	0.55 – 24.5
Mean Fe_2O_3/CaO ratio	0.54			

The silica (SiO_2) content varies from 1.25 to 93.3%, averaging 51.1%, while aluminum oxide (Al_2O_3) ranges from 0.01 to 32.8%. Calcium oxide (CaO) concentrations fluctuate between 0.15 and 39.1% (average 12.0%), reflecting the alternation of skarn zones and the enclosing marbles. Iron oxide (Fe_2O_3) content is moderate (0.55–24.5%, average 6.5%), with a Fe_2O_3/CaO ratio of approximately 0.54, indicating an intermediate stage of iron enrichment in the skarns.

These ratios allow distinguishing two end-member compositional types of skarns:

1. Silicate skarns, characterized by elevated SiO_2 and Al_2O_3 contents, corresponding to garnet–pyroxene associations;

2. Calcium (magnetite) skarns, distinguished by higher CaO and Fe_2O_3 contents, often accompanied by amphibole–chlorite assemblages of the retrograde stage.

Preliminary studies of trace elements (V_2O_5, Cr_2O_3, NiO, CuO, ZnO, Mo, W, PbO, and U) revealed enrichment in transition and chalcophile elements near the ore-bearing horizons. Vanadium, chromium, and nickel show a positive correlation with Fe_2O_3, reflecting the influx of hydrothermal fluids. Molybdenum and tungsten occur sporadically, with local anomalies exceeding 0.01%, consistent with late hydrothermal overprints.

The observed chemical variability supports a multistage model of skarn evolution: 1) Prograde stage – formation of garnet–pyroxene assemblages under conditions of elevated silica (SiO_2 > 60%, Al_2O_3 > 20%); 2) Main magnetite stage – iron metasomatism, characterized by FeO + Fe_2O_3 contents of about 20–25%, decreased SiO_2, and increased CaO; 3) Retrograde stage – hydration and formation of epidote, chlorite, and amphibole, accompanied by redistribution of Cu, Zn, and Mo. This sequence is typical for iron-skarn systems of Central Kazakhstan and is similar in mineral evolution to the Zhuantobe and Bapy deposits.

Chemical analysis was performed on 141 samples collected from drill holes W-1, W-2, and W-3 across the skarn zone of the Karaulken deposit. The program included determination of major oxides (SiO_2, Al_2O_3, CaO, Fe_2O_3, MnO) as well as a range of trace elements, aimed at distinguishing silicate, calcium, and ore-bearing (magnetite) skarn varieties. The sample set covers both weakly altered zones and ore-bearing intervals with elevated iron content.

Summary statistics for the main components are presented below (Table 2).

Table 2. Results of chemical analysis (major oxides, %).

Parameter	SiO_2	Al_2O_3	CaO	Fe_2O_3	MnO
Count (n)	141	137	141	141	137
Mean	38.9	6a	10.16	30.13	0.55
Std. dev.	19.94 6.82 8.79 19.28				2.49
Min	1.93	0.028	0.12	2.22	0.0046
25th percentile	26.04	1.74	4.64	12.66	0.075
Median	41.36	3.67	7.94	28.03	0.126
75th percentile	51.83	10.61	13.00	46.79	0.173
Max	85.68	29.54	39.26	71.20	17.00

The table shows that the main variable component is Fe_2O_3: its content ranges from 2.2 to 71.2%, with an average of 30.1%, clearly indicating the presence of well-developed magnetite skarns and, in places, almost ore-grade intervals. Silica (SiO_2) varies over a very wide range (1.9–85.7%), reflecting the alternation of silicate (garnet–pyroxene), partially quartz-bearing, and strongly iron-rich zones. The average CaO content is 10.2%, but in some samples it reaches 39%, which is characteristic of calcium skarns formed on carbonate protoliths.

The combined behavior of Fe_2O_3, SiO_2, and CaO allows distinguishing three geochemical–mineralogical facies within the section:

1. Silicate (prograde) skarns – elevated SiO_2 (50–85%), low to moderate CaO (4–12%), and Fe_2O_3 generally <15%. These correspond to early garnet–pyroxene formations at the contact with the intrusive body.

2. Calcium–iron skarns – CaO 12–25%, Fe_2O_3 20–45%, SiO_2 20–50%. This represents the main ore-bearing part of the section, associated with iron metasomatism in carbonate rocks.

3. High-iron (magnetite) skarns / ore layers – Fe_2O_3 > 45–50% (up to 70%), with decreased SiO_2 and, in places, lower CaO. These intervals are traced across multiple drill holes and are interpreted as zones of focused upward transport of Fe-bearing hydrothermal fluids.

Notable MnO anomalies (up to 17% in individual samples) indicate local involvement of Fe–Mn metasomatism, typical of the retrograde stage and zones of mixing between oxidized and reduced solutions.

Comparison of the chemical analyses with previously conducted spectral analyses shows that the chemical data capture a later, more ore-rich stage of skarn system formation. Spectral analysis defines the broader skarn halo with an average Fe_2O_3 of ~6.5%, while the chemical composition reflects the actual ore-bearing core with an average Fe_2O_3 of ~30%. These observations suggest a probable multistage evolution of the Karaulken deposit: 1) early silicate skarn formation; 2) calcium–iron metasomatism; 3) retrograde re-deposition and mobility of Cu, Zn, and Mo. This model is fully consistent with the conceptual understanding of iron-skarn systems in Central Kazakhstan and is comparable to the Zhuantobe and Bapy deposits.

The Karaulken deposit is a contact iron-skarn body formed within Devonian carbonate–siliceous sequences under the influence of presumably Fe-bearing metasomatic fluids of the dioritic association. Mineralization is structurally controlled by sublatitudinal faults of the Akbastau zone, which served as the main channels for metasomatic fluid circulation and ore-body formation.

Although internal potential for resource growth is limited, the deposit still has zones for further expansion: 1) flanking extensions of sublatitudinal ore bodies, especially at intersections with meridional faults; 2) deep horizons below the current exploration level, where hidden ore lenses may develop; 3) local “blind” bodies within carbonate packages, partially masked by weak oxidation in the near-surface zone.

The deposit is characterized by a stable geological model, high technological suitability of magnetite ores for magnetic beneficiation, and manageable mining–technical risks. The future value of the project depends on: 1) the quality and detail of further exploration to convert resources into reserves; 2) optimization of the plant processing scheme, taking into account variations in P_2O_5 content; 3) careful planning of the initial stages of open-pit mining, considering the presence of a supergene "cap" that can affect ore density, strength, and beneficiation.

A comprehensive assessment of structural, mineralogical, and geometallurgical factors allows Karaulken to be considered a representative model of Late Paleozoic contact–metasomatic iron-skarn systems in Central Kazakhstan, of interest both for scientific research and for practical tasks in mineral resource forecasting and evaluation.

Discussions. The ore mineralization of the Karaulken deposit exhibits a combination of features typical of a hydrothermal–metasomatic (skarn) system: 1) spatial localization of ore bodies at contacts of marbleized carbonates and siliceous–carbonate sequences intruded by dioritic dikes; 2) development of garnet–pyroxene–epidote skarns; 3) predominance of magnetite with subordinate hematite; 4) presence of retrograde alterations (quartz veining, carbonation, formation of iron hydroxides).

This sequence of stages and the zonation of secondary alterations are consistent with studies such as those at the Campiglia Marittima deposit (Tuscany) (Vezzoni et al., 2023), where late-stage fluids reworked pre-existing skarn associations, leading to telescoping of sulfide mineralization onto early iron-rich stages.

In a regional context, Karaulken fits the model of a Late Paleozoic contact iron-skarn system in Central Kazakhstan. The Akbastau fault zone served as the main fluid drainage channel, controlling the formation of elongated sub-latitudinal ore bodies along contacts between rocks of contrasting reactivity. This structure is similar to ore-controlling systems described for the high-grade skarn deposit of Goudian (Lucy block, North China Craton), where mineralization age has been determined by $^{40}Ar/^{39}Ar$ geochronology of phlogopite (Li et al., 2024).

From a geometallurgical perspective, the predominance of magnetite (>90% Fe) explains the high magnetic susceptibility of the ores and the efficiency of magnetic separation (concentrate yield ~58%, Fe ~46%, recovery >83%). This aligns with patterns observed in other skarn deposits, where beneficiation efficiency directly correlates with magnetite content and its textural state. Similar relationships were established for the Beizhan (Western Tien Shan) and Makin (Fujian Province) deposits, where the chemistry and isotopic composition of magnetite reflect the evolution of ore-forming processes (Feng et al., 2024; Yi et al., 2024).

Elevated P_2O_5 (~3%) and partial hematitization in the near-surface horizons present technological limitations. As shown in comparable studies, late fluid stages and oxidation processes modify magnetite composition (in elements V–Ti–Cr–Mn) and create vertical zonation of ore facies, requiring adaptive beneficiation schemes – selective desilication and combined magnetic–flotation methods (Kolm et al., 1975; Zhang et al., 2021).

The observed vertical zonation–transition from a hematite–limonite "cap" to mixed magnetite ± hematite zones, and then to massive/veined magnetite in skarns– is typical for many global analogues. Telescoping and remobilization by late-stage fluids were also documented at Campiglia (Vezzoni et al., 2023). Practically, this means that at the early stages of open-pit mining, oxidized, heterogeneous ores may be encountered, requiring different grinding degrees and separation settings.

Compared to other deposits in the West Balkhash iron ore district, Karaulken is distinguished by the more pronounced role of contact-skarn processes and simpler ore-body morphology. A larger proportion of carbonate substrate and less-developed magnetite–quartz veins provide stronger magnetic response, explaining the high efficiency of detailed ground magnetic surveys. Similar approaches are actively discussed in recent studies of the Zhuantobe deposit.

The results are consistent with modern research employing microanalytical methods (LA-ICP-MS, Fe–O isotopes, $^{40}Ar/^{39}Ar$) to refine genetic models and predictive criteria (Zhao and Zhou, 2015). Applying these techniques to Karaulken would allow testing: 1) changes in fluid composition at the boundary between prograde and retrograde stages; 2) oxidation gradients in the supergene zone; 3) synchronicity of mineralization with diorite emplacement and deformations of the Akbastau zone. This would improve the accuracy of fluid flow forecasting and the localization of "blind" ore lenses.

The proposed model of skarn evolution is based primarily on geological, petrographic, mineralogical, and geochemical observations. Direct constraints on the physicochemical parameters of ore-forming fluids, including temperature, salinity, and fluid sources, were not obtained in the present study because fluid inclusion and stable isotope analyses (O, H, S) were beyond the scope of the investigation. Therefore, interpretations regarding hydrothermal fluid evolution should be regarded as preliminary and require further verification using isotope geochemistry and fluid inclusion studies.

Conclusion. The Karaulken deposit represents a typical Late Paleozoic contact–metasomatic system of the West Balkhash iron ore district in Central Kazakhstan, formed through the interaction of granitoid intrusions with Devonian carbonate–siliceous sequences under conditions of active fluid metasomatism controlled by the sub-latitudinal faults of the Akbastau zone. Similar systems are known beyond the region–for example, Beizhan and Goudian (Lucy block, North China Craton) (Li et al., 2024; Feng et al., 2024; Yi et al., 2024), where magmatism and structure jointly controlled ore localization and metasomatic processes.

The ore bodies, lens-shaped and sub-tabular (2–76 m thick), are composed of magnetite with subordinate hematite and pyrite and are characterized by an average Fe content of ~29% ($Fe_2O_3 \approx 40\%$), high magnetic susceptibility, and high beneficiation performance (recovery >83%), comparable to results reported for the Makin and Campiglia Marittima skarns (Vezzoni et al., 2023; Yi et al., 2024).

From a geometallurgical perspective, Karaulken demonstrates a close relationship between mineralogical composition, magnetite chemistry, and ore processing behavior, consistent with modern studies of micro-mineralogy and isotopes in skarn systems of the Northwest Balkhash iron ore district (Korobkin et al., 2025).

Karaulken can be regarded as a reference model of iron–skarn mineralization in Central Kazakhstan, displaying all evolutionary stages in sequence–from contact metamorphism to retrograde hydrothermal and supergene transformation. An integrated approach, combining structural, mineralogical, and geophysical analyses, provides a foundation for refining metallogenic models and predictive criteria in the exploration of skarn deposits across the Central Asian Fold Belt.

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