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STUDY OF GEOLOGICAL FEATURES OF IRON ORE DEPOSITS IN KAZAKHSTAN TO IDENTIFY PROSPECTIVE REGIONS

This article is devoted to the study of the state of the resource base of iron ore raw materials in Kazakhstan, as well as to the overview of the main geological and industrial types of iron ore deposits in the Republic. During the study, the territorial division of the country's iron resources into regions was made, the geological features of occurrence were considered and the most promising regions of the country were identified in terms of increasing balance reserves of iron ores.

The paper analyzes the geological conditions of localization of ore bodies, structural and tectonic factors of their formation, as well as spatial variability of the qualitative characteristics of ores. In total, 4 main geological and industrial types of iron deposits are identified, which are spatially distributed unevenly. It is noted that significant iron reserves are located in Eastern, Southern and Western Kazakhstan, however, only a few deposits in the region are economically viable for extraction at present. In turn, Central Kazakhstan is considered as one of the key objects of further geological research, since its stratiform deposits of siliceous-carbonate formation are characterized by the presence of complicated geological and structural features, and their potential can make a significant contribution to the replenishment of iron mineral resources.

Particular attention is paid to the application of spatial modeling and geostatistical analysis methods, which allow objectifying assessment of reserves, clarifying spatial patterns of mineral substance distribution and increasing reliability of ore content forecast. The obtained results can be used to optimize the strategy of geological exploration and scientific substantiation of the prospects for the development of iron ore deposits in Central Kazakhstan.

Keywords: *iron ore deposits, deposits of Central Kazakhstan, ferrous metallurgy, stratiform iron deposits, geological and industrial types of iron ore deposits, reserve appraisal, modeling*

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Introduction

Ferrous metallurgy is one of the most important industries as it produces the main structural goods and materials. Iron ore raw materials, necessary for the production of iron and steel, are used in all areas of industry and are the most common metallic mineral.

According to the United States Geological Survey (USGS), global iron ore reserves are estimated at about 180 billion tons, with resources estimated at 800 billion tons [1]. Kazakhstan, ranked 10th, accounts for about 1.1% of the total global reserves, which also places it among the leaders among the CIS countries (3rd place after Russia and Ukraine). **Figure 1** shows a diagram of global iron ore reserves per countries as of 2022 [1, 2].

As the key element in steel production, iron ore supplies the world's largest metals market, worth $1 trillion per year, and is the foundation of global infrastructure [2, 3]. As a result of growing demand for steel products, traditional high-grade iron ore reserves are being significantly depleted, and many new iron ore deposits with lower grades and more complex mineralogy are being developed. The iron ore market is one of the largest in Kazakhstan; according to the National Statistics Bureau of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, the volume of production in the republic amounted to 487.6 billion tenge in the first half of 2021 alone.

As follows from **Fig. 2**, the bulk of explored iron ore reserves are concentrated in the Kostanay Region of Northern Kazakhstan, where exploitation is carried out mainly by open-pit mining. However, a significant portion of the Region's industrial deposits are approaching late stages of development, which limits the potential for further growth of balance reserves and requires the search for new promising sites.

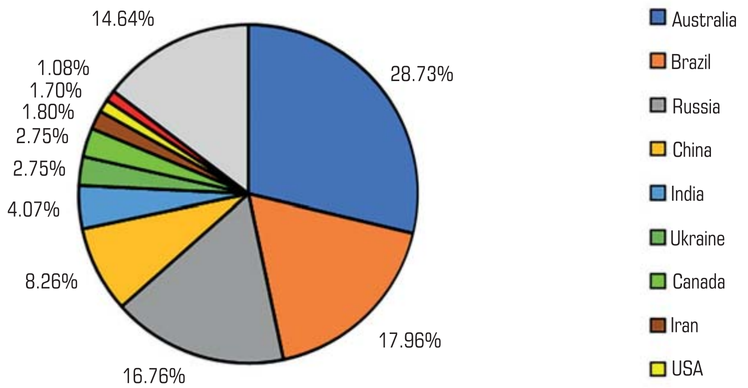

Fig. 1. World iron ore reserves per countries as of 2022

Main geological and industrial types of iron ore deposits in Kazakhstan

According to the classification of the State Commission on Mineral Reserves (GKZ), about a third of all explored iron ore reserves in Kazakhstan belong to categories A and B, which indicates a high degree of their exploration. Approximately 50% of iron ore raw materials are in industrial development, and if current production volumes are maintained, the reserve supply is estimated for a period of about 70 years [4, 5].

The bulk of iron ore reserves are concentrated in Northern Kazakhstan. However, due to the long-term operation of these objects and their approach to the late stages of development, the predicted dynamics of reserves indicates a gradual reduction in ores available for open-pit mining. In this regard, the study of Central Kazakhstan as a region with significant potential for the development of deep-lying ore deposits is becoming a strategically important area. Modern geological and geophysical studies indicate that the largest iron deposits in Kazakhstan have already been explored in detail, and further growth of balance reserves is possible only through detailed geological exploration, revaluation of previously discovered deposits and additional exploration of ore occurrences. In this context,

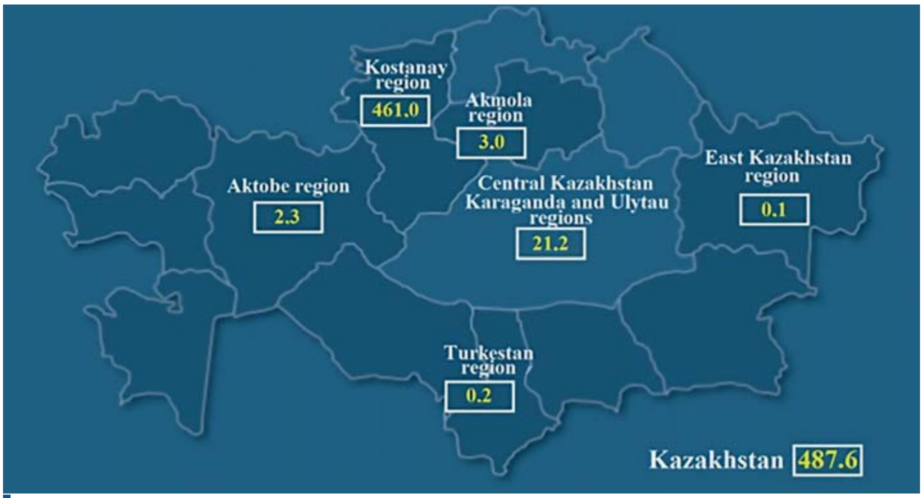

Fig. 2. Volume of iron ore production (billion tenge) per regions (Bureau of National Statistics of the Republic of Kazakhstan)

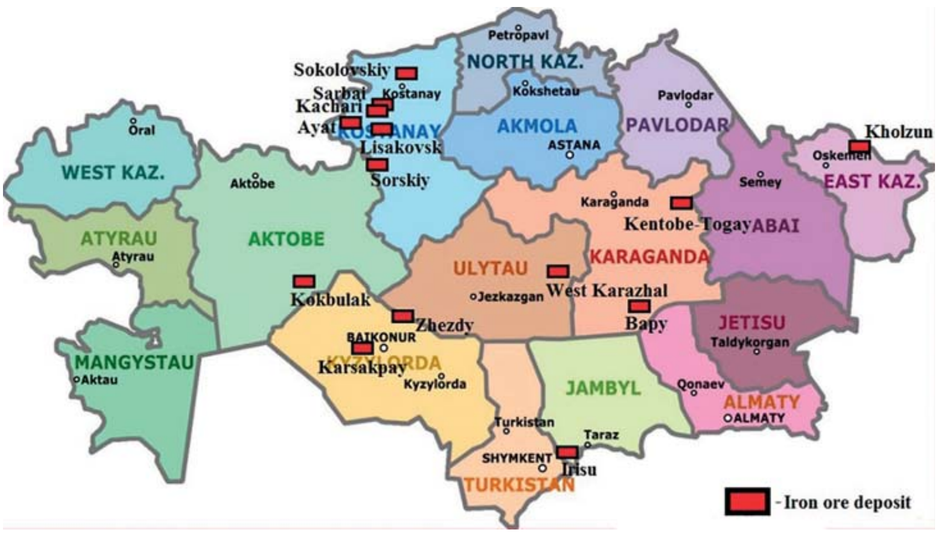

Fig. 3. The main iron ore deposits of Kazakhstan

modern approaches to structural analysis, modeling and forecasting of the spatial distribution of ore bodies are of particular importance, which allows us to clarify the parameters of deposits and increase the efficiency of their development.

In geological and industrial terms, iron ore deposits in Kazakhstan are divided into four main types (**Table 1**): magmatic, stratiform contact-metamorphosed, skarn and sedimentary. Each of these types has its own genetic, structural and mineralogical features, which necessitates the use of differentiated methods for their assessment and development.

Magmatic iron deposits in Kazakhstan have a limited spread. The main manifestations of this type of ore are localized within the Sakmar, Ulytau and Valeryanovsky structural–formational zones.

Stratiform deposits are associated with volcanogenic-sedimentary processes, accompanied by the accumulation of iron-containing components in sedimentary basins and their subsequent metamorphic processing. Deposits of this type are established in rocks of the Proterozoic, Ordovician (middle and upper), Devonian (middle and upper) and Lower Carboniferous ages, where ore bodies occur according to the main stratigraphic horizons. Tectonically, stratiform deposits of Kazakhstan are divided into two types: riftogenic deposits associated with ophiolitic magmatism, and deposits formed in riftogenic structures with carbonate filling and trachybasalt-trachyliparite magmatism [4].

Figure 3 shows the largest iron ore deposits in Kazakhstan:

Skarn deposits were formed as a result of metasomatic transformation of primary volcanogenic-sedimentary ore complexes in contact with igneous intrusions. [6]. Basically, the largest ones include iron ore deposits of the Valerianovskaya Vize-Serpukhov volcanogenic-sedimentary strata, which territorially belongs to the Kostanay region [7].

Sedimentary deposits are widespread and are one of the main sources of ore raw materials on a global scale [7–9]. In the country, they are mainly localized in the Kostanay region, where the largest objects of this type are the Lisakovskoye and Ayatskoye deposits.

A brief overview of the country's main iron ore deposits by region

West Kazakhstan

Iron ore deposits in Western Kazakhstan are predominantly of the skarn type and are small in scale. Total reserves of this type of ore are estimated at approximately 400 million tons. Some deposits contain high-quality ores suitable for direct use without preliminary enrichment, which makes their profitable development possible using artisanal mining methods. The region has significant predicted resources of ferrous magmatic ores. Within the Velikhovsky South and Goryunovskoye deposits, total resources are estimated at more than 400 million tons, but the ores are characterized by low iron content and the presence of impurity elements such as titanium and vanadium, which complicates their processing [9]. Sedimentary deposits in Western Kazakhstan have relatively high geological reserves, exceeding 2.300 million tons, with an average iron content of 35–45% (for example, the Kokbulak deposit). However, ores of this type are characterized by an increased phosphorus content, which significantly reduces their industrial significance due to the high cost of processing and the complexity of metallurgical processing [4, 7].

Table 1. Main geological and industrial types of iron ore deposits by region

Region	Predominant geological and industrial types of deposits	Main deposits
Northern Kazakhstan	Sedimentary, skarn and igneous	Kacharskoe, Sokolovskoe, Sarbayskoe, Lisakovskoe
Central Kazakhstan	Stratiform, contact-metamorphosed	Kentobe, Karazhal, Bapy
Western Kazakhstan	Sedimentary and skarn	Velikhovskoye, Kokbulak
South Kazakhstan	Scarn	Irisuyskoe
East Kazakhstan	Stratiform contact–metamorphosed	Kholzunskoe, Markakolskoe

North Kazakhstan

North Kazakhstan is the main iron ore region of the country and plays a key role in providing the mineral resource base of both Kazakhstan and neighboring countries. Balance reserves of iron ore in the region in categories A, B and C1 of which more than 8.500 million and about 9.000 million tons in category C2. Over 7.000 million tons of iron ore are classified as off-balance reserves. Most of the deposits, including those currently being developed, are concentrated in Turgay. Deposits and iron ore occurrences outside the region are small and, in general, are not economically viable for development. An exception are some objects within the Stepnyak zone, which can be involved in development using small-scale mining methods. The most numerous deposits in the region are skarn-type deposits. The iron ore reserves of deposits of this type exceed 7.500 million tons, including more than 5.000 million tons in categories A, B and C1 and about 2.000 million tons in category C2. Currently, the large Kacharskoye and Sokolovskoye, Sarbayskoye and Kurzhunkulskoye deposits are being developed in the region [10].

Several dozen medium- and small-size skarn-type deposits have been explored with varying degrees of detail. The ores are predominantly magnetite, transformed into martite varieties in the oxidation zone, with iron content ranging from 30–35 to 60%. The ores are easy to beneficiate. Some of the ores are suitable for use in the metallurgical process without beneficiation, and their associated components (sulfur, cobalt) are not extracted [8, 9].

Sedimentary iron ore deposits of Northern Kazakhstan are less numerous, but their reserves exceed the resources of skarn deposits by more than two times and amount to about 16.500 million tons, of which 3.500 million tons belong to categories A, B and C1, and more than 6.200 million tons belong to category C2. The main reserves are concentrated within the Lisakovsky and Ayatsky deposits [11]. The ores of sedimentary deposits are represented by hydrogoethite, hydrogoethite-siderite–lepidochlorite and glauconite varieties, characterized by low quality and complexity of enrichment [12]. The average iron content in ores is 35–37%, phosphorus (P_2O_5)—up to 0.4%, sulfur (S)—up to 0.7%. Geological reserves of iron ores of magmatic deposits of Northern Kazakhstan are estimated at 965 million tons, with more than 945 million tons concentrated within the Davydovskoye deposit, located near the Kacharskoye deposit. However, the ores of these deposits have a low iron content (24–33%) and are currently not being developed [4, 7].

South Kazakhstan

South Kazakhstan are represented mainly by small objects, the total explored and probable reserves of which do not exceed 550 million tons. The only large object is the Irisui skarn deposit, containing about 350 million tons of explored reserves of iron ore by industrial categories. The remaining deposits in the region remain poorly studied, and their probable resources vary from several million to the first tens of millions of tons. Stratiform deposits are represented by small poorly studied objects, the total probable reserves are about 60 million tons. Sedimentary deposits are known in the Paleogene deposits in the Kyzylorda region and in the Jurassic deposits in the South Kazakhstan region. The probable reserves of sedimentary ores in the region are 70 million tons [9].

East Kazakhstan

Iron ore deposits in Eastern Kazakhstan are few in number and mainly belong to the stratiform contact-metamorphosed type. Skarn occurrences are extremely rare and have insignificant reserves, not exceeding several hundred thousand tons of rich ores. The total reserves of stratiform deposits in the region are about 1.400 million tons, of which 1.200 million tons are concentrated within the Kholzun deposit. A feature of this type of ores is the high content of phosphorus associated with apatite, which complicates their processing. Total reserves of P_2O_5 at the Kholzunskoye and Markakolskoye deposits amount to 51 million tons [7, 9].

Central Kazakhstan

Central Kazakhstan ranks second in iron ore reserves, but is relatively unexplored compared to the northern region. Currently, the Kentobe–Togay group of iron ore deposits and the iron-manganese deposits of the Atasu group are being developed here, which are the main sources of ore raw materials for the metallurgical production of the Karaganda Metallurgical Plant (JSC Qarmet). The total ore reserves of the region are estimated at 7.000 million tons, but most of them are off-balance or predicted (about 6.000 million tons) [9]. More than half of all reserves of Central Kazakhstan are concentrated within the stratiform deposits of the siliceous-carbonate formation.

Deposits of magmatic and sedimentary types in Central Kazakhstan are found in limited quantities and remain poorly studied. Their main concentration is noted in the north-eastern part of the region, within the Irtysh iron ore basin, which occupies an area of 70–80 thousand km^2. The predicted reserves of brown ironstone oolitic ores are estimated at 1.500–2.000 million tons [4].

Skarn iron ore occurrences in the region are relatively numerous, but have insignificant reserves, varying from hundreds of thousands to a few million tons. The rich ores of these deposits (50–55%) are of interest for artisanal mining, but require clarification of their industrial significance [4]. Central Kazakhstan is characterized by significant reserves of iron ores localized in regionally metamorphosed stratiform deposits confined to the Precambrian complexes of the Shu-Ili (Zhuantobe–Gvardeyskoye) and Karsakpai (Balbraun, Keregetas) regions [8]. The total estimated reserves of iron ores of this type exceed 2.000 million tons. However, the ores of these deposits are difficult to enrich [13], which limits their industrial development in the near future.

Contact-metamorphosed stratiform deposits are widespread in Central Kazakhstan. They are represented mainly by small and medium-sized objects, the total reserves of which are about 1.000 million tons, of which more than 600 million tons are forecast and off-balance. Currently, industrial exploitation of high-quality ores of the Kentobe deposit is underway, the reserves of which ensure a stable supply of metallurgical enterprises. However, most other deposits of this type require additional study in order to clarify their industrial potential. Of great importance among the iron ore objects of Central Kazakhstan are stratiform iron-manganese deposits confined to Upper Famennian sediments. The main reserves are concentrated in the Atasuysky district, where the established resources are estimated at 700 million tons, of which more than 520 million tons are industrial categories. The most significant deposit is Karazhal, which contains over 505 million tons of high-quality ores. According to the quality of the ores, stratiform deposits are divided into two groups: jasperoid–andesite–basalt formation and siliceous-carbonate (terrigenous-siliceous-carbonate) formation. Ores of the first group are of no economic interest due to their low technological and qualitative characteristics. Ores of the second group, mainly of Famennian age, are magnetite, weakly siliceous, and mainly of high quality and technological characteristics [9]. Stratiform deposits of Central Kazakhstan are characterized by a wide stratigraphic distribution and were formed in different geological eras, which determines their mineral composition, structure and industrial significance. Depending on the age and lithofacies conditions of formation, three main chronological levels of localization of iron ore deposits are distinguished: Proterozoic, Ordovician and Upper Devonian. Each of these levels has specific features that affect the industrial value of the ores and the prospects for their development. **Table 2** presents their characteristics [7, 9].

The analysis showed that the stratiform iron ore deposits of the region demonstrate significant differences in geological structure, mineral composition and industrial potential. The most valuable are the ores of the Upper Devonian and Ordovician levels, which are distinguished by more favorable conditions for extraction and processing. At the same time, Proterozoic deposits, despite their widespread occurrence, remain the least promising due to the low quality of ores and the complexity of their

Table 2. Chronological levels of localization of stratiform iron ore deposits in Central Kazakhstan

Chronological level	Geological characteristics	Mineral composition	Main deposits	Industrial importance
Proterozoic	Ferruginous quartzites of the jasper–basalt formation	Hematite ores, high silica content	Guards, Keregetas, Balbraun	Low iron content, difficult to enrich, economically unprofitable
Ordovician (middle)	Siliceous–basaltic–terrigenous formation	Ferruginous quartzites subjected to contact metamorphic changes	Karatas, Bapy	Increased iron content, improved enrichment, promising for development
Upper Devonian (Famennian)	Siliceous–carbonate formation with basalt-trachyliparite volcanics	Magnetite ores	Karazhal, Kentobe–Togay, a number of small objects	Large industrial deposits, an important source of iron

Table 3. Iron ore reserves of Kazakhstan per regions

Region	Iron ore reserves, Mt	Total reserves, %	Comment
Northern Kazakhstan	35.000	75.7	The main iron ore region, includes the largest deposits (Kacharskoe, Sokolovskoe, Lisakovskoe)
Central Kazakhstan	7.000	15.1	Stratiform deposits, a significant part of the reserves are off-balance and forecast
Western Kazakhstan	2 300	5.0	Sedimentary and igneous deposits are presented (Kokbulak, Velikhovskoye Yuzhnoye)
East Kazakhstan	1.400	3.0	Mainly stratiform deposits (Kholzunskoye, Markakolskoye)
South Kazakhstan	550	1.2	Small deposits, the main one is Irisuyskoye
Total	46 250	100.0	Total reserves of iron ore in Kazakhstan

enrichment. Thus, the choice of Central Kazakhstan as the main object of research is due to a number of scientific, economic and geological factors that distinguish this region from other territories of the Republic:

- The main deposits of the Northern region are already in the late stages of exploitation, which leads to a decrease in the possibilities for the growth of balance reserves. In Central Kazakhstan, on the contrary, there are significant forecast and off-balance resources that require additional geological exploration work to accurately determine their parameters and industrial suitability.
- Central Kazakhstan is characterized by a complex structure and tectonics, which was formed under the influence of many geological processes (sedimentation, metamorphism, contact-metamorphic transformations). This complexity determines the presence of spatial variations in the morphology of ore bodies and their mineralogical composition, which is of interest for the development of new methodological approaches in geostatistical analysis and forecasting of reserves.
- Since the main deposits of Kazakhstan are already in the stage of active development and their reserves are gradually being depleted, Central Kazakhstan acts as a strategic alternative for further provision of the country's metallurgical industry with raw materials.

Due to the high structural variability and complexity of ore formation in Central Kazakhstan, the use of modern geostatistical methods and 3D modeling is particularly relevant. The development and implementation of such approaches will not only clarify the parameters of ore body occurrence, but also improve the accuracy of reserve forecasts, which is critical for making investment and operational decisions [14, 15].

- The study of Central Kazakhstan allows us to identify previously unaccounted patterns of formation of stratiform iron ore deposits, which enriches theoretical concepts in the field of mineral geology. The results of the study can be used to optimize geological exploration in Kazakhstan and develop methodological approaches applicable to similar objects in other regions of the world [15–17].

Global context and unique features of stratiform deposits of Central Kazakhstan

Stratiform iron ore deposits located in Central Kazakhstan are a special type of ore formations formed under conditions of sedimentary and volcanogenic–sedimentary processes in the Devonian and Early Carboniferous periods. Their geological structure differs significantly from the sedimentary and skarn deposits of Northern Kazakhstan, which makes the region an important object of geological study. Similar ore formations are found in various parts of the world, including the Labrador Belt (Canada), Kursk Magnetic Anomaly (Russia), Hammersley (Australia), Kiruna (Sweden), Sishen and Nkout (South Africa and Cameroon) [18, 19]. However, stratiform deposits of Kazakhstan have a number of features caused by tectonic processes and metasomatic changes, which determines their scientific and industrial significance [20–22].

Comparison with world analogues shows that the stratiform deposits of Central Kazakhstan have a high degree of structural dislocation caused by the superposition of several deformation phases. Unlike the relatively stable layers of ferruginous quartzites characteristic of the Labrador Belt and deposits in Australia (Hammersley) [21, 22], the stratiform ore bodies of Central Kazakhstan were formed in a zone of intense tectonic movements. As a result of the impact of several deformation phases, they have a complex morphology caused by tectonic ruptures, facies variability and metasomatic transformations. Such a structure requires an individual approach to the assessment of reserves and forecasting methods.

A special characteristic of iron ore deposits in Central Kazakhstan is their close connection with siliceous–carbonate complexes that have undergone deep metamorphic processing. This has led to the formation of a complex mineralogical composition, which complicates the application of traditional methods of interpreting geological data. Mineralogical heterogeneity and the complexity of structural control require new methods of spatial modeling. World practice of developing stratiform deposits indicates the need to introduce modern methods of analyzing the spatial distribution of ore bodies. In particular, integrated approaches are actively used in Canada and Australia, including detailed structural interpretation, geochemical mapping and the use of digital models for estimating reserves [22–24].

Kentobe–Togay iron ore region is one of the key objects of Central Kazakhstan, possessing significant, but at the same time insufficiently studied resource potential. Despite the presence of identified reserves, many parameters of ore bodies, such as morphology, spatial variability and geochemical features, require further clarification. From the point of view of structural-geological analysis, the area belongs to the Upper Devonian level, characterized by complex lithological-facies zonality caused by the interaction of sedimentary and magmatic processes. Such conditions led to the formation of stratiform iron ore deposits with pronounced variability of thickness and qualitative composition, which requires the use of modern assessment methods for correct forecasting of reserves. The mineralogical composition of the ores of the area is also of particular interest, since magnetite and magnetite-hematite varieties predominate, a significant part of which has undergone metasomatic changes, which affects their technological enrichment and processing. To illustrate the described geological features,

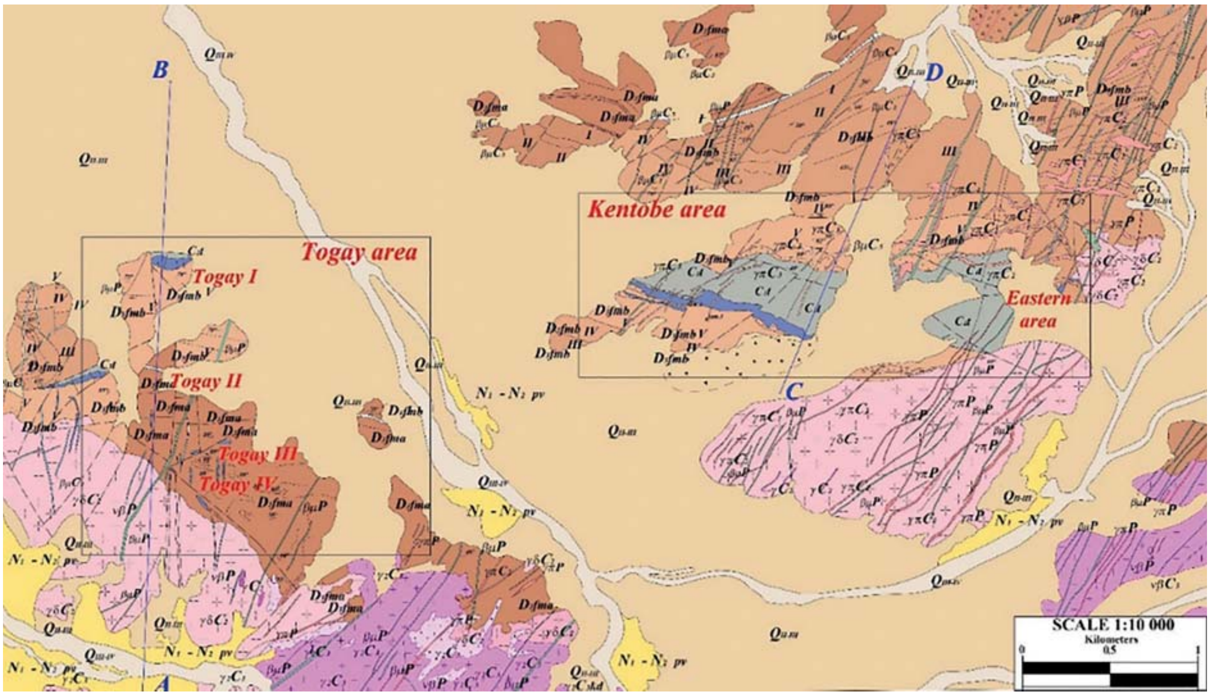

Fig. 4. Geological map of the Kentobe–Togay deposit

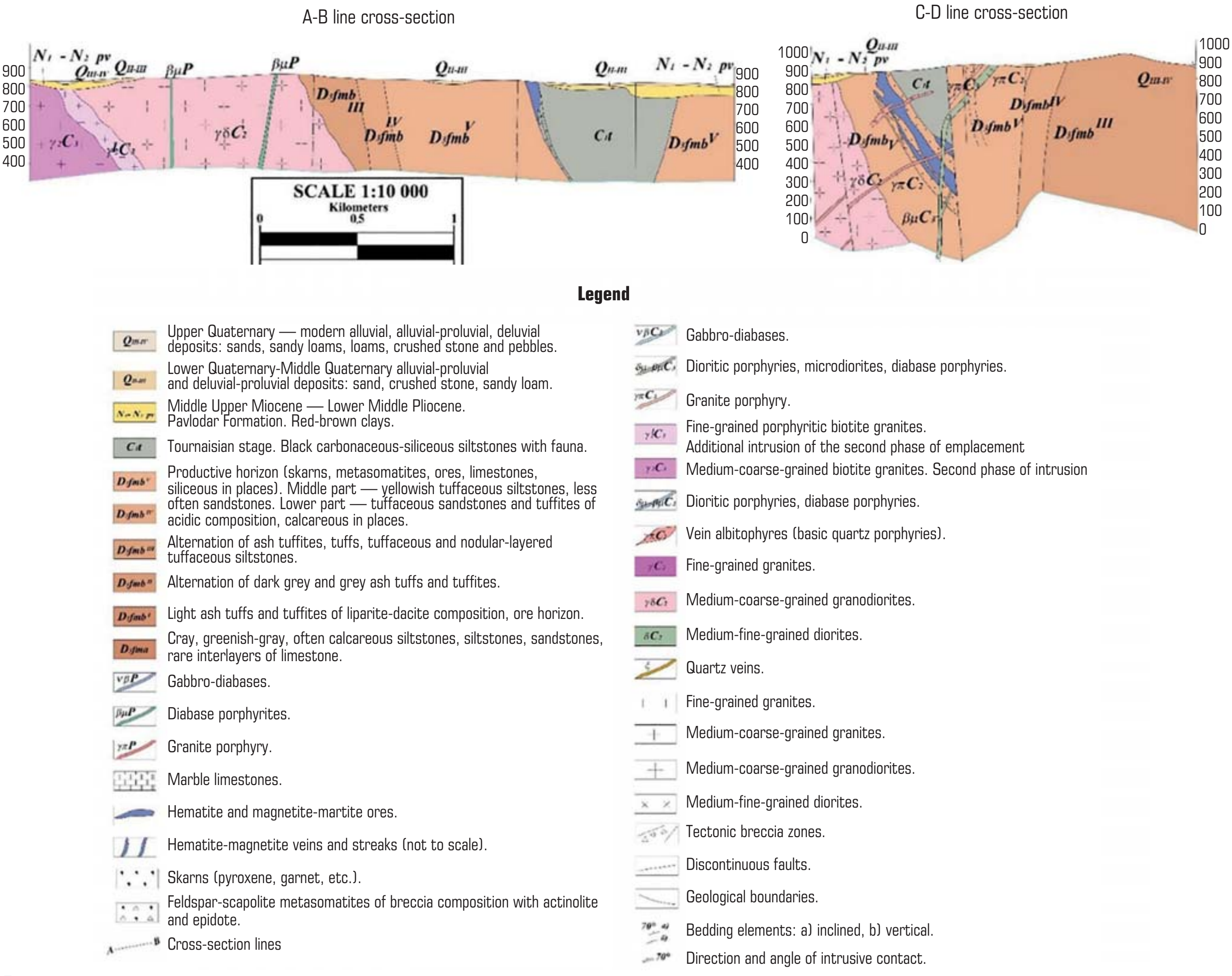

Fig. 5. Geological sections along lines A–B and C–D

an image of a geological map (**Fig. 4**) and a geological section (**Fig. 5**) of the Kentobe deposit are provided as an example, demonstrating the structural-tectonic complexity, the nature of the occurrence of ore bodies and the spatial distribution of minerals.

These graphic materials serve as clear evidence of the need for further research to clarify the parameters of ore bodies and optimize reserve assessment methods, which is of critical importance for the formation of scientifically based strategies for the development of complex ore systems in Central Kazakhstan.

Conclusions

The conducted analysis showed that the iron ore base of Kazakhstan is characterized by an uneven distribution of reserves by regions, which determines the strategic priorities for further geological exploration. In total, 4 main geological and industrial types of iron ore deposits have been identified: magmatic, skarn, stratiform contact-metamorphosed and sedimentary. Different types of deposits are promising for industrial development in each region. The bulk of explored reserves are concentrated in Northern Kazakhstan, which has long been the main supplier of iron ore raw materials for the country's metallurgical industry. However, the high degree of development of the region's deposits and the gradual depletion of reserves available for open-pit mining require the search for new promising territories to expand the mineral resource base. The spatial distribution of the country's iron ore resources is given in **Table 3**, which reflects the volumes of reserves by region, their share in the total volume and the main geological and industrial features [9].

Central Kazakhstan is considered a key region for further research, as its stratiform deposits remain understudied, and their predicted and off-balance reserves can significantly increase the country's resource potential. Given the complex structural structure of the deposits and the high variability of the morphology of ore bodies, the use of modern 3D modeling and geostatistical analysis methods will improve the accuracy of reserve assessment, minimize uncertainties and form scientifically based approaches to their development.

Of particular importance in this context is the Kentobe–Togay region, which is one of the most promising objects in Central Kazakhstan. Its stratiform deposits are confined to Upper Devonian siliceous-carbonate formations and are characterized by significant variability in the composition and morphology of ore bodies. The introduction of advanced methods for interpreting geological data, forecasting reserves and mineralogical analysis will not only allow for an objective assessment of the region's ore potential, but also for developing new scientific approaches to the development of complex iron ore systems [16, 17].

Thus, further study of Central Kazakhstan, and in particular the Kentobe–Togay region, is not only of practical but also of fundamental scientific interest, since it will allow identifying new patterns of formation of stratiform iron ore deposits of siliceous-carbonate. The obtained results can be used to create geological and genetic models of similar deposits, which will increase the efficiency of prospecting and exploration work in the region, and the introduction of modern technologies for analysis, modeling and forecasting of ore content will increase the efficiency of geological exploration and create scientifically based strategies for involving understudied deposits in industrial development.

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