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GEOLOGICAL CHARACTERISTICS AND ENVIRONMENTAL ASPECTS OF THE DEVELOPMENT OF THE ZHUANTOBE SKARN IRON ORE DEPOSIT

Abstract

Skarn iron ore deposits represent a significant component of the global iron resource base, yet their development is commonly associated with substantial environmental disturbance due to large-scale open-pit mining. This study presents an integrated geological and geoecological assessment of the Zhuantobe skarn iron ore deposit (Central Kazakhstan), focusing on the relationship between ore-forming processes and environmental response under active mining conditions. The research combines geological, mineralogical, geochemical, geophysical, and long-term environmental monitoring datasets (2018–2025). Ore bodies are characterized by complex morphology controlled by fault systems and multistage skarn evolution, including prograde (garnet–pyroxene) and retrograde (magnetite–sulfide) assemblages. Environmental monitoring indicates a systematic reduction in anthropogenic impact, including a decrease in dust load (>40%), soil iron content (~40%), and CO₂ emissions (~35%). The results demonstrate that the implementation of integrated environmental protection measures effectively stabilizes environmental parameters within permissible limits. The study provides a framework linking geological structure with environmental performance and proposes a set of transferable strategies for sustainable development of skarn iron ore deposits.

Keywords: skarn deposits, iron ores, geoecology, environmental monitoring, sustainable mining, Central Kazakhstan.

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Introduction

Modern approaches to subsoil use require not only detailed geological investigation but also comprehensive assessment of environmental impacts associated with mineral resource development [1, 2]. This is particularly important for skarn iron ore deposits, which are typically located in tectonically complex zones and involve large-scale open-pit mining [3–5].

The Zhuantobe iron ore deposit, located within the Northwestern Balkhash metallogenic region of Central Kazakhstan (Fig. 1), represents a typical skarn system formed in contact zones between intrusive rocks and carbonate sequences.

The aim of this study is to provide an integrated geological and environmental assessment of the Zhuantobe deposit and evaluate the effectiveness of environmental protection measures implemented during its development. The objectives include characterization of geological structure and ore mineralization; analysis of mineralogical and textural features of ores; assessment of environmental conditions based on monitoring data (2018–2025); evaluation of mitigation measures and development of recommendations. Scientific novelty lies in the integration of geological and environmental datasets, enabling assessment of the relationship between ore-forming processes and environmental response during mining.

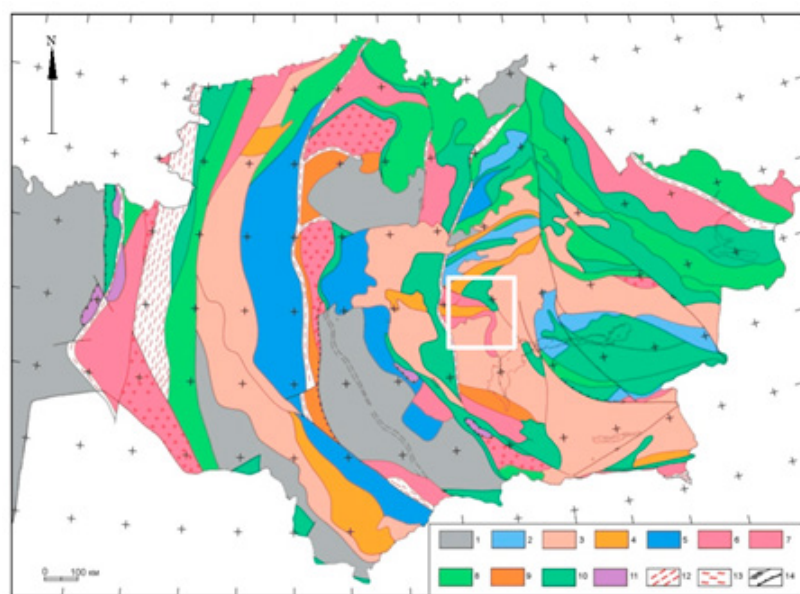


Figure 1 – Tectonic zoning scheme of the Paleozoic regions of Kazakhstan [6] (the iron ore district of the northwestern Balkhash area is highlighted by a white rectangle). The legend identifies 14 tectonic units: (1) Tectonic depressions, (2) Fragments of forearc terraces, (3) Volcanic and volcano-plutonic belts, (4) Rifts, (5) Folded strike-slip-thrust zones, (6) Cratonic terranes subjected to weak granitization, (7) Cratonic terranes with granite-gneiss domes, (8) Fragments of volcanic island arcs, (9) Fragments of riftogenic basins, (10) Collisional sutures, (11) Ophiolitic allochthons, (12) Zones of transform sutures and suture zones, (13) Schist zones, (14) Collisional and post-collisional faults.

Materials and methods

The geological investigation included field mapping, structural analysis, and drilling with continuous core recovery. A representative dataset of ore and host rock samples ($n \approx 300-400$) was analyzed.

Petrographic analysis was conducted using transmitted light microscopy (Leica DM750), while mineralogical composition was determined by X-ray diffraction (XRD). Geochemical analyses of major and trace elements were performed using spectrometric and ICP-based methods.

Magnetic surveys were used to delineate structural controls and ore zones. Gamma logging was applied to assess natural radiation background and identify potential anomalies [4].

Environmental assessment was based on long-term monitoring conducted from 2018 to 2025 [1, 2, 7–10]. Monitoring included:

- ◆ atmospheric parameters (dust load, CO₂ emissions);
- ◆ soil characteristics (pH, Fe content);
- ◆ surface and groundwater quality;
- ◆ biodiversity indicators.

Measurements were conducted at fixed monitoring stations on an annual (or quarterly) basis, ensuring temporal consistency of the dataset.

A semi-quantitative evaluation framework based on national environmental standards was applied. Baseline conditions (2018) were compared with post-mitigation data (2025), allowing assessment of environmental response to implemented measures.

Results

The Zhuantobe deposit is located within the Atasu–Mointy anticlinorium and is associated with the Dzhungar–Balkhash Hercynian folded system (Fig. 2). The geological structure is characterized by a combination of volcanic, sedimentary, and intrusive rocks, affected by fault systems of NW and sublatitudinal orientation.

Ore bodies exhibit complex morphology and are spatially controlled by fault zones. Mineralization is dominated by magnetite, with subordinate hematite, pyrite, and chalcopyrite [4, 6].

The evolution of the deposit reflects a multistage skarn-forming process:

- ♦ prograde stage: garnet–pyroxene assemblages;
- ♦ retrograde stage: magnetite, sulfides, and hydrothermal alteration.

This mineralogical zonation directly influences ore quality and environmental behavior.

During the development of the Zhuantobe deposit, a set of measures will be implemented to prevent contamination of soil–vegetation cover and water bodies (Fig. 3). In addition, the introduction of modern engineering solutions for waste storage and reclamation is planned in order to prevent their release into the environment. Regular environmental monitoring confirms that all parameters remain within the permissible limits established by the legislation of the Republic of Kazakhstan [1, 7–13].

The study area is characterized by semi-arid climatic conditions and low biological productivity. The absence of permanently established protected species reduces ecological sensitivity; however, mining activities remain a significant source of disturbance.

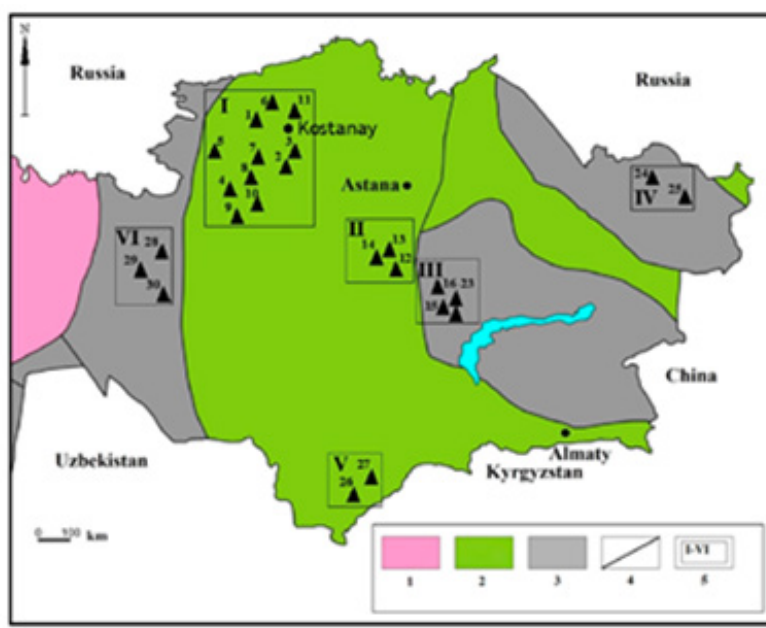


Figure 2 – Scheme of the main tectonic units and distribution of major industrial types of iron ore deposits in Kazakhstan: (1) East European Craton; (2, 3) Kazakh segment of the Central Asian Fold Belt: (2) Caledonian fold systems, (3) Hercynian fold systems; (4) geological boundaries; (5) outlines of iron ore districts. The deposits are grouped into six regions: I – Northern Torgay: 1. Kachar, 2. Sarbai, 3. Sokolov, 4. Lisakov, 5. Ayat, 6. Aleshino, 7. Lomonosov, 8. South Sarbai, 9. Sor, 10. Shagyrol, 11. Korzhynkol; II – Central Kazakhstan: 12. Karazhal, 13. Ushkatyn, 14. Bolshoi 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. Velikhovskoye, 29. Kokbulak, 30. Taldy-Espe. III marks the position of the North Balkhash ore region, which hosts the Zhuantobe deposit

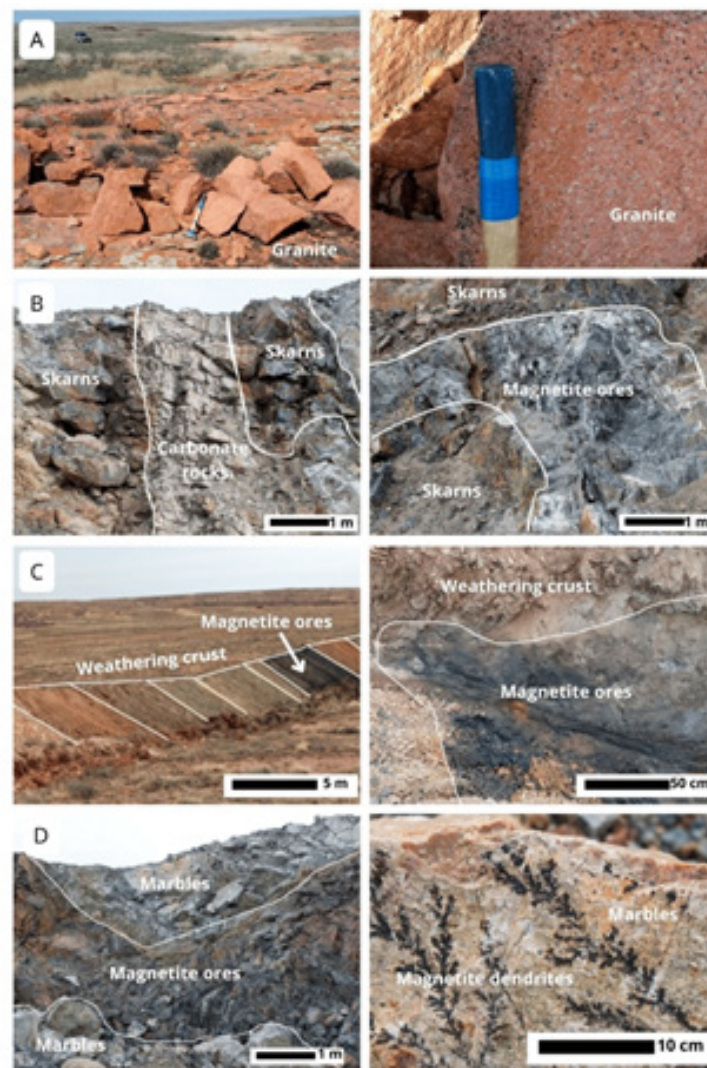


Figure 3 – Outcrops of rocks (A – granites) and mine workings (B–D) at the Zhuantobe deposit subject to reclamation after the completion of exploration and mining operations. B, D – open pit; C – exploration trench

The main physical factor is noise from mining equipment and vehicles. However, the remoteness of the deposit from settlements (more than 50 kilometers) makes its impact negligible. Technological processes capable of causing vibration or electromagnetic pollution are absent [13–15]. Gamma logging data show that the radiation background of the site is within natural values (15–80 microrentgen/hour).

The Zhuantobe deposit area belongs to semi-desert steppes with extremely sparse vegetation (feather grass, cereals, shrubs, juniper). Red Book plant species are absent, which is confirmed by the conclusion of the Forestry and Wildlife Inspection. The fauna is represented by typical steppe and desert species: rodents, birds of prey, and small passerines. Near water bodies, rare species listed in the Red Book of Kazakhstan are occasionally encountered, such as saiga, golden eagle, and great bustard [1, 7, 8].

Radiation background values (15–80 $\mu\text{R/h}$) fall within natural limits.

The graph (Figure 1) demonstrates a reduction in all major pollution indicators. Of particular importance is the increase in the pH of water resources, which indicates a decrease in acidity previously caused by sulfide oxidation and the inflow of wastewater. The presented data show that: (1) the pH of

water resources has increased, confirming a reduction in acidity due to sulfide oxidation; (2) the iron content in soils has decreased by almost 40%; (3) dust load has been reduced by more than twofold; and (4) CO₂ emissions have declined by 35% relative to 2018.

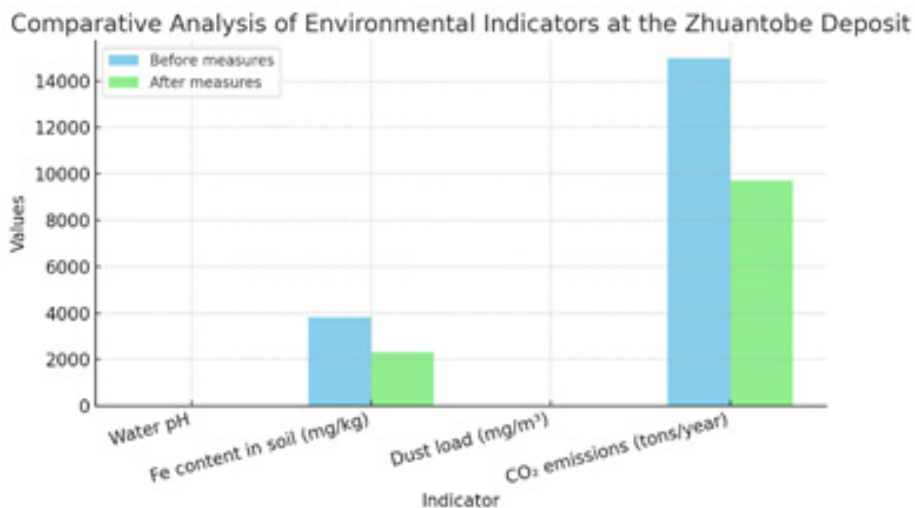


Figure 4 – Comparative analysis of environmental indicators at the Zhuantobe deposit

The environmental aspect associated with geological and mining operations for iron ore development is regulated by the legislation of the Republic of Kazakhstan. In this regard, all relevant regulatory documents were applied in the present study. These include works addressing problems of ecology and geoecology, as outlined in [1, 2, 16–21].

The development of the Zhuantobe skarn iron ore deposit represents an example of a comprehensive approach to involving medium and small-scale mineral resource objects of the Northwestern Balkhash ore region into exploitation, taking into account both economic and environmental factors. The geological exploration and geoecological studies conducted allow a number of conclusions to be drawn, significant both for assessing anthropogenic impacts on the environment and for optimizing design solutions at all stages of development.

From a geological perspective, the Zhuantobe deposit possesses a number of favorable characteristics: a thin overburden, stability of host rocks, and the possibility of open-pit mining with minimal volumes of capital works [7, 8, 22–24]. The physical and mechanical properties of the ores and host rocks require drilling and blasting preparation, which, in turn, necessitates strict control of dust emissions and vibration impacts on the environment [25–27].

The mineralogical composition of the ores (magnetite with admixtures of pyroxene, garnet, serpentine, biotite, and other minerals) and their monometallic nature simplify the processing scheme but require monitoring of associated elements (Ti, V, Mn, Cr, etc.), which, although not exceeding critical thresholds, may affect the environmental characteristics of waste [28–30].

Geoecological studies confirmed that the background concentrations of mobile forms of heavy metals, as well as the content of natural and technogenic radionuclides within the deposit area, do not exceed established standards. This provides grounds to conclude that, if project solutions are followed, the development of the deposit will not lead to significant contamination of environmental components.

It should be noted, however, that during operation, 542 hectares of land previously used as low-productive pastures will be disturbed. This requires reclamation with a sanitary–hygienic orientation, reflecting the responsible attitude of the subsoil user to ecosystem restoration. The planned pit depth (up to 266 m) and area (75.6 ha) dictate the necessity of a well-designed reclamation system upon completion of mining activities.

In terms of the area's water balance, the low water content of the productive horizon, poor surface runoff development, and arid climate minimize the risk of water contamination. Nevertheless, an important condition remains strict control of the quality of discharged pit waters and compliance with measures for water resource protection.

The flora and fauna of the area do not include ecologically valuable or protected species, eliminating risks for rare and endangered biodiversity. This simplifies environmental justification procedures and reduces biodiversity-related risks.

Thus, analysis of the obtained data makes it possible to conclude that, provided all project-based environmental measures are implemented, the development of the Zhuantobe deposit can proceed with minimal environmental impact. The mining and exploitation of the object are technically and environmentally justified, and the established ecological database provides a basis for subsequent monitoring of environmental conditions during the deposit's operation.

Table 1 summarizes environmental parameters before and after the implementation of mitigation measures.

Table 1 – Environmental parameters before (2018) and after (2025) mitigation measures

Parameter	2018	2025
Soil pH	6.2	7.1
Dust load (mg/m ² /day)	3800	2300
Fe in soil (%)	0.42	0.18
CO ₂ emissions (t/year)	15000	9700

A consistent decrease in pollution indicators is observed, indicating the effectiveness of environmental management strategies.

Discussion

The results demonstrate a strong relationship between geological structure and environmental response. Fault-controlled ore bodies influence:

- ◆ spatial distribution of mining operations;
- ◆ localization of environmental impacts;
- ◆ pathways of contaminant migration.

The observed reduction in environmental impact is attributed to:

- ◆ improved waste management systems;
- ◆ dust suppression technologies;
- ◆ controlled water discharge;
- ◆ progressive land reclamation.

A comparative analysis with the Zhuantobe skarn deposit confirms that similar geological settings exhibit comparable environmental responses, supporting the general applicability of the proposed approach.

Importantly, the integration of geological and environmental datasets allows prediction of environmental risks based on geological parameters, which represents a significant advancement in geoecological assessment.

Conclusion

This study demonstrates that the sustainable development of skarn iron ore deposits requires the integration of geological understanding with comprehensive environmental management approaches. The results indicate that geological structure plays a fundamental role not only in controlling ore

formation but also in influencing the spatial distribution and intensity of environmental impacts. Long-term environmental monitoring confirms a significant reduction in anthropogenic pressure, particularly in terms of dust load, soil contamination, and atmospheric emissions, reflecting the effectiveness of the implemented mitigation measures. These findings highlight that properly designed environmental protection strategies ensure compliance with regulatory standards and contribute to the stabilization of ecosystem conditions in mining areas.

From a practical perspective, sustainable mining of skarn deposits can be achieved through the implementation of continuous environmental monitoring throughout the entire mining lifecycle, the application of advanced dust suppression and emission control technologies, strict management and treatment of mine and waste waters, and systematic reclamation of disturbed lands. Furthermore, the integration of environmental considerations at the early stages of geological exploration is essential for minimizing long-term impacts. The proposed approach provides a transferable and scalable framework for environmentally responsible mining, applicable to skarn deposits in Central Kazakhstan and analogous geological settings worldwide.

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