


STRATIGRAPHIC AND STRUCTURAL FEATURES OF IRON ORE DEPOSITS OF THE SILICO-CARBONATE FORMATION OF CENTRAL KAZAKHSTAN

¹V.O. Kim , ²V.V. Cheskidov , ³A.D. Maussymbayeva , ¹R.K. Madisheva , ¹F.M. Issatayeva  ,
¹N.S. Askarova , ¹S.B. Imanbaeva 

¹Non-profit joint stock company «Abylkas Saginov Karaganda Technical University», Karaganda, Kazakhstan,

²University of Science and Technology MISIS, Moscow, Russian Federation,

³University of Illinois at Urbana Champaign, Champaign, USA

 Correspondent-author: adambeikova_farid@mail.ru

The article considers stratigraphic and structural features of the formation of iron ore deposits confined to the siliceous-carbonate formation of Central Kazakhstan, using the Kentobe-Togai group as an example. A comprehensive analysis of lithological and stratigraphic conditions, morphology of ore bodies, fault systems and metasomatic transformation zones is carried out. Key patterns are revealed: confinement of ore bodies to reactive carbonate-siliceous deposits of the Upper Devonian and Lower Carboniferous; formation of ores in zones of contact metamorphism during the intrusion of granitoids; the active role of faults in the localization and segmentation of deposits; pronounced vertical zoning of the mineral composition of ores; as well as parametric heterogeneity of bodies. These features taken together form unique geological systems, where mineralization is regularly controlled by stratigraphy and structure.

Geological maps, sections and three-dimensional wireframe models of the Kentobe-Togay group deposits with visualization of ore bodies, faults and intrusions are presented, demonstrating a close spatial relationship between tectonics, magmatism and iron enrichment. The results emphasize the need to apply modern methods of 3D modeling, geostatistical interpolation and structural analysis in assessing the resources of such deposits, and also show that the established patterns are universal and can be applied to predict and model similar objects.

Keywords: central Kazakhstan, iron ores, stratiform deposits, siliceous-carbonate formations, tectonics, metamorphism, 3D modeling of iron ore deposits.

СТРАТИГРАФИЧЕСКИЕ И СТРУКТУРНЫЕ ОСОБЕННОСТИ ЖЕЛЕЗОРУДНЫХ МЕСТОРОЖДЕНИЙ КРЕМНИСТО-КАРБОНАТНОЙ ФОРМАЦИИ ЦЕНТРАЛЬНОГО КАЗАХСТАНА

¹В.О. Ким, ²В.В. Ческидов, ³А.Д. Маусымбаева, ¹Р.К. Мадисева, ¹Ф.М. Исатаева , ¹Н.С. Асқарова,
¹С.Б. Иманбаева

¹Некоммерческое акционерное общество «Карагандинский технический университет им. Абылкаса Сагинова», Караганда, Казахстан,

²Университет науки и технологий МИСИС, Москва, Российская Федерация,

³University of Illinois at Urbana Champaign, Champaign, USA,
e-mail: adambeikova_farid@mail.ru

В статье рассмотрены стратиграфические и структурные особенности формирования железорудных месторождений, приуроченных к кремнисто-карбонатной формации Центрального Казахстана, на примере Кентобе-Тогайской группы. Проведён комплексный анализ литолого-стратиграфических условий, морфологии рудных тел, систем разломов и зон метасоматического преобразования. Выявлены ключевые закономерности: приуроченность рудных тел к реакционно-способным карбонатно-кремнистым отложениям верхнего девона и нижнего карбона; формирование руд в зонах контактного метаморфизма при внедрении гранитоидов; активная роль разломов в локализации и сегментации залежей; выраженная вертикальная зональность минерального состава руд; а также параметрическая неоднородность тел. Эти признаки в совокупности формируют уникальные геологические системы, где минерализация закономерно контролируется стратиграфией и структурой.

Представлены геологические карты, разрезы и трёхмерные каркасные модели месторождений Кентобе-Тогайской группы с визуализацией рудных тел, разломов и интрузий, демонстрирующие тесную пространственную взаимосвязь между тектоникой, магматизмом и железообогащением. Полученные результаты подчёркивают необходимость применения современных методов 3D-моделирования, геостатистической интерполяции и структурного анализа при оценке ресурсов таких месторождений, а также показывают, что установленные закономерности обладают универсальностью и могут быть применены для прогнозирования и моделирования аналогичных объектов.

Ключевые слова: центральный Казахстан, железные руды, стратиформные месторождения, кремнисто-карбонатные формации, тектоника, метаморфизм, 3D моделирование железорудных месторождений.

ОРТАЛЫҚ ҚАЗАҚСТАННЫҢ КРЕМНИЙ-КАРБОНАТТЫ ҚАБЫЛДАУЫНЫҢ ТЕМІР РУДАЛАРЫНЫҢ СТРАТИГРАФИЯЛЫҚ ЖӘНЕ ҚҰРЫЛЫМДЫҚ ЕРЕКШЕЛІКТЕРІ

¹В.О. Ким, ²В.В. Ческидов, ³А.Д. Маусымбаева, ¹Р.К. Мадешева, ¹Ф.М. Исатаева✉, ¹Н.С. Асқарова, ¹С.Б. Иманбаева

¹ «Әбілқас Сағынов атындағы Қарағанды техникалық университеті» коммерциялық емес акционерлік қоғамы, Қарағанды, Қазақстан,

² Ғылым және технология университеті МИСИС, Мәскеу, Ресей Федерациясы,

³ University of Illinois at Urbana Champaign, Champaign, USA,
e-mail: adambekova_farid@mail.ru

Мақалада Кентөбе-Тоғай тобы мысалында Орталық Қазақстанның кремнийлі-карбонатты формациясымен шектелген темір кен орындарының қалыптасуының стратиграфиялық және құрылымдық ерекшеліктері қарастырылған. Литологиялық және стратиграфиялық жағдайларға, кен денелерінің морфологиясына, жарылу жүйелеріне және метасоматикалық трансформация аймақтарына кешенді талдау жүргізілді. Негізгі заңдылықтар анықталды: кен денелерінің жоғарғы девон және төменгі карбонның реактивті карбонатты-кремнийлі кен орындарымен шектелуі; гранитоидтарды интродукциялау кезінде контактілі метаморфизм аймақтарында кендердің түзілуі; кен орындарын оқшаулау мен сегменттеудегі ақаулардың белсенді рөлі; кендердің минералдық құрамын айқын тік аудандастыру; сонымен қатар денелердің параметрлік гетерогенділігі. Бұл ерекшеліктер минералдану стратиграфиясы мен құрылымымен дәйекті түрде бақыланатын бірегей геологиялық жүйелерді құрайды.

Кентөбе-Тоғай топтық кен орындарының геологиялық карталары, көлденең қималары және 3D сым каркас модельдері, тектоника, магматизм және темірдің байыту арасындағы тығыз кеңістіктік байланысын көрсететін кен денелері, бұзылулар мен интрузиялар бейнеленген. Алынған нәтижелер мұндай кен орындарының ресурстарын бағалауда 3D модельдеудің, геостатистикалық интерполяцияның және құрылымдық талдаудың заманауи әдістерін қолдану қажеттілігін көрсетеді, сондай-ақ белгіленген заңдылықтардың әмбебап екенін және ұқсас объектілерді болжау және модельдеу үшін қолдануға болатынын көрсетеді.

Түйін сөздер: Орталық Қазақстан, темір рудалары, стратиформды кен орындары, кремнийлі-карбонатты түзілімдер, тектоника, метаморфизм, темір кен орындарының 3D модельдеу.

Introduction. Iron is one of the fundamental elements of modern civilization, underlying the production of steel and, consequently, all branches of industry, construction and infrastructure. Iron ore deposits, as the main source of this metal, play a strategically important role in ensuring economic sustainability and industrial development. Their study entails not only practical benefits for mining, but also fundamental scientific tasks related to the reconstruction of geological processes, forecasting ore bodies and understanding the conditions of their formation [1].

At the global level, a significant diversity of genetic types of iron ore deposits has been established, including magmatic, hydrothermal, sedimentary, skarn and stratiform [2]. Among them, stratiform iron ore deposits are of particular interest, since they are often associated with stable stratigraphic horizons and are characterized by a high degree of homogeneity and predictability of the occurrence of ore bodies. Particularly valuable scientific data are provided by cases of contact-metamorphosed stratiform deposits, which combine elements of sedimentary, metasomatic and tectonic mineralization.

Central Kazakhstan, which is part of the Caledonian and Hercynian fold belt, is characterized by complex tectonic development and a high diversity of volcanogenic-sedimentary and intrusive complexes. Siliceous-carbonate formations are widespread in this region, on the basis of which stratiform iron ore deposits have developed, subjected to contact metamorphism and skarn-hornfels transformations. These geological conditions create favorable prerequisites for the formation of significant iron reserves, especially in areas of interaction of granitoid intrusions with carbonate and terrigenous strata of Devonian and Carboniferous age [2, 3].

A typical example of such geological systems is the Kentobe-Togay group of deposits located in the Karkaraly district of the Karaganda region. These deposits are localized along exocontacts of granodiorite intrusions and demonstrate stratiform placement of ore bodies metamorphosed under contact conditions. Magnetite, martite, hematite and skarnoid ores are noted here, combined with elements of gold-copper and polymetallic mineralization [geological report]. Stratigraphically, ore-bearing horizons are confined to siliceous-carbonate and terrigenous-shale deposits that have undergone metasomatic changes.

Despite the high resource significance of the region, the geological exploration of deposits in Central Kazakhstan is significantly inferior to similar objects in Northern Kazakhstan, where the largest magnetite deposits in the country are concentrated [2, 3]. This makes research in the field

of stratigraphic and structural patterns of Central Kazakhstan particularly relevant both from the point of view of replenishing the mineral resource base and for the development of scientific ideas about ore-forming systems in conditions of complex metamorphism and tectonic activation.

This study is aimed at a comprehensive analysis of stratigraphic and structural factors contributing to the formation of iron ore mineralization within the siliceous-carbonate formations of Central Kazakhstan. The main objective is to identify key geological features that can serve as indicators for forecasting and evaluating new ore objects in similar geological conditions.

Materials and methods. The main object of the study is the Kentobe-Togay group of iron ore deposits located in the Karkaraly region of Central Kazakhstan. Geological objects are represented by stratiform and contact-metamorphosed iron ore bodies confined to the Upper Devonian and Lower Carboniferous siliceous-carbonate formations. The initial basis for the analysis was the data of a geological survey on a scale of 1:10,000, materials from drilling exploration wells, geophysical and geochemical studies.

For spatial analysis and geological modeling, specialized software packages were used: Leapfrog and Surpac, in which the following were performed:

- construction of three-dimensional wireframe models of ore bodies, intrusions and faults;
- integration of stratigraphic, structural and lithological data;
- preparation of models for the development of a block model and interpolation of useful component contents.

Additionally, the study used comparative materials on a similar iron ore object, in particular on the Western Karazhal deposit, in order to substantiate the applicability of the developed approaches to other similar geological systems in the region [4].

Geological setting of the region. Central Kazakhstan is one of the most geologically complex territories of the country, where elements of Caledonian and Hercynian folding, intrusive and

volcanogenic-sedimentary complexes of different ages and compositions, as well as numerous fault and folded structures are combined. These factors determine the diversity of the lithological section and the presence of favorable conditions for the formation of iron ore bodies, especially stratiform and contact-metamorphosed ones.

Ore-bearing complexes are mainly associated with Devonian and Lower Carboniferous deposits, including alternation of limestones, dolomites, siliceous and silty-clayey shales. These rocks often form stable stratigraphic horizons in which ore bodies are localized. The most productive strata are those that have undergone contact metamorphism during the intrusion of granitoids (granodiorites, biotite granites), forming exocontact zones of mineralization.

Key iron ore bodies are confined to the zones of interaction of Devonian siliceous-carbonate deposits with intrusions, which causes the development of hornfels, skarns and skarnoids. In the contact zones, recrystallization processes, replacement of carbonates by iron-containing minerals (magnetite, martite, hematite), and the formation of parageneses with the participation of garnet, epidote, pyroxene and amphibole occur. The most typical mineralization is found within the Karkaraly, Atasuy, Karsakpai and Ereimentau structural-formational zones. The Karkaraly region contains the Kentobe, Sarybulak, Togay objects, characterized by lenticular, sheet-like and columnar ore bodies occurring along stratigraphic and tectonic contacts [5].

The tectonic architecture of the region is represented by a system of sublatitudinal and submeridional faults that control both the placement of intrusions and the position of ore bodies. Most deposits are oriented along tectonic faults and are localized in fault intersection zones. Dislocations, strike-slip and normal faults, often accompanied by zonal skarnoid belts, play an important role. The lithological and formational features of iron-bearing strata vary from siliceous-dolomite and calcareous-siliceous to carbonate-shale complexes. Upper Devonian (Famennian) and Lower Carboniferous (Tournaisian-Vashkir) deposits

often contain interlayers of ferruginous quartzites, siderite and hematite ores that have undergone late metamorphic and tectonic reworking. In these rocks, ores often retain a stratified texture and a layered-lenticular morphology, indicating the stratiform nature of mineralization [5].

The morphology of ore bodies varies from extended layers to isometric lenses, occurring both in parallel and diagonal positions to the layering of the host rocks. In the central part of the region, there are also skarnified bodies - ore stocks, vein bodies replacing carbonate rocks along cracks and zones of fragmentation. The characteristics of ore-bearing complexes of iron ore deposits in central Kazakhstan by formations are presented in Table 1.

An example is the Kentobe deposit, where ore bodies are localized at the contact of granodiorites with terrigenous-carbonate rocks, are sheet-like bodies of magnetite and martite, with oxidation zones (up to 20-25 m), enriched in hematite. A complex combination of stratigraphic and tectonic factors is noted here - ore bodies gravitate towards zones of shear, folding and intrusion of intrusions. In some cases, as in the Sarybulak and Togai areas, iron ore bodies appear against the background of significant lithological variability, partial re-mineralization and the presence of associated elements (barite, manganese, polymetals). This indicates a multi-stage ore formation and a combination of sedimentation, metamorphogenic and hydrothermal processes. In Fig.1 shows a geological map of the Kentobe-Togai ore field, which shows the connection of ore-bearing deposits with siliceous-carbonate rocks of the Devonian and Carboniferous ages, as well as the numerous tectonic faults in the mineralization zone [5].

In the environment of Central Kazakhstan, green shale and low-temperature regional metamorphism facies are also widely represented, which limits the development of typical skarns, but promotes the formation of skarnoids and iron micro-redeposition zones. These processes play an important role in the mobilization and redistribution of iron, as well as in the formation of ore bodies with transitional texture and heterogeneous mineral composition [6].

Stratigraphic features. The largest iron ore

Ore bodies have a clear stratigraphic confinement to certain levels of the sedimentary section, often controlled by primary lithological heterogeneity and facies zonality. The bulk of the ores are localized in zones of alternating carbonate and terrigenous rocks, where favorable conditions are created by porosity, reactivity of rocks and the presence of fluid paths. Stratigraphically,

mineralization mainly develops:

- in the lower part of the Devonian strata - among dolomites and siliceous limestones,
- in the middle part - among alternating shales and thin-banded carbonate rocks,
- at contacts with intrusions, where zones of regressive skarnization and iron redeposition are observed.

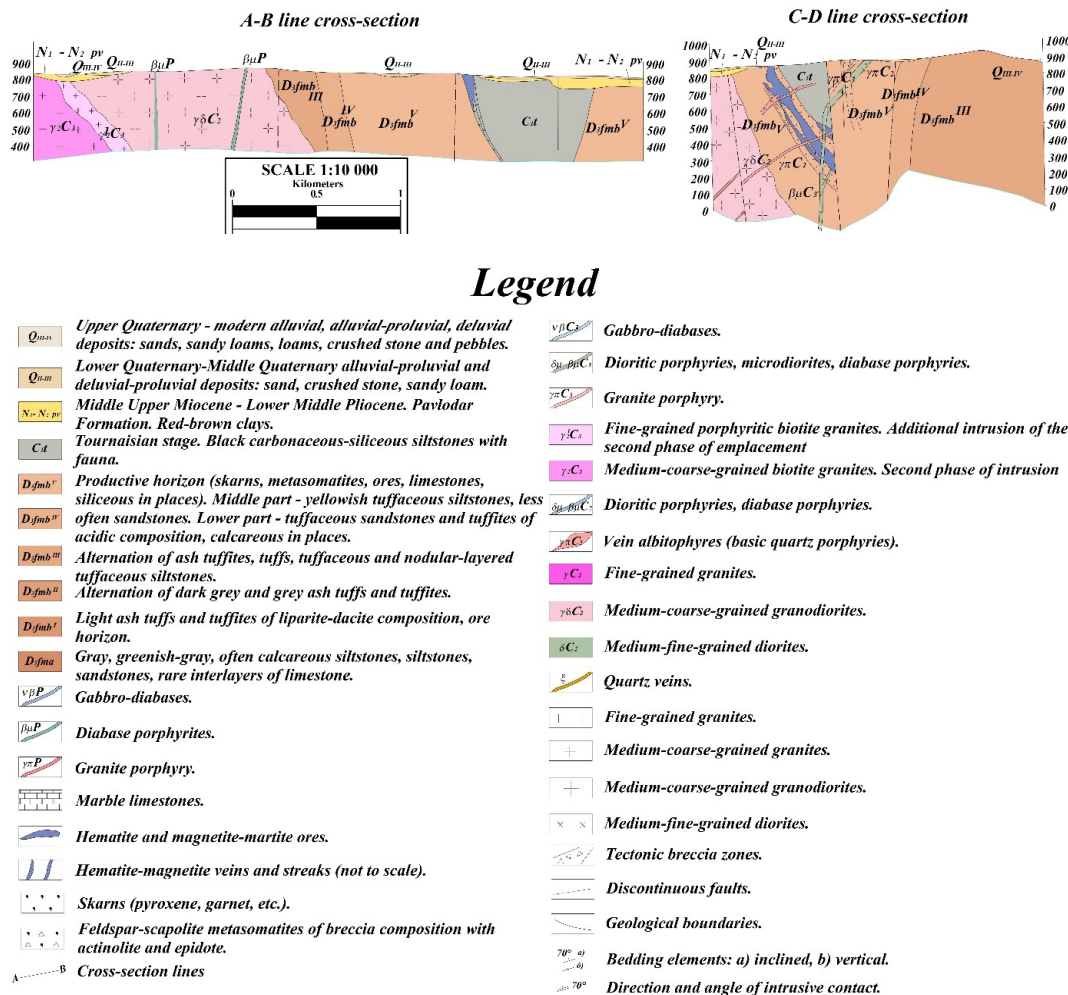


Fig.2 - Generalized stratigraphic section of the Kentobe-Togai area with the identification of ore-bearing horizons with conventional designations. Scale 1:10,000

The stratiform deposits of the region are characterized by a gently inclined orientation of the ore bodies, repeating the structure of the host rocks. In the most studied areas, an ore-bearing horizon with a thickness of 3 to 20 m can be traced, containing lenticular or sheet-like deposits of magnetite and martite ores. At the same time,

a clear zonality is noted - from poor ores on the periphery to rich ones in the central parts of the bodies [6].

Oxidized zones are formed in the upper horizons, where the original magnetite ores are transformed into martite and hematite ores. Deeper in the section, primary magnetite ores predominate. These

changes illustrate the vertical zoning caused by the conditions of oxidation and hydrothermal redistribution of components. The lower horizons are sometimes characterized by a transition to skarnoids and more intense metasomatic changes. The features of the rhythm of sedimentation (fine interbedding), the presence of organic residues, porous textures and increased content of ferrous minerals in sedimentary strata - all this creates the prerequisites for sedimentary and hydrothermal-sedimentary genesis of ores, with subsequent contact-metamorphic re-formation.

Of particular interest is the comparison of the stratigraphic conditions of the Kentobe-Togai group with another well-studied object of Central Kazakhstan, the West Karazhal deposit, located within the Atasu iron ore zone. This deposit, like Kentobe, is confined to Upper Famennian deposits, represented by siliceous-carbonate and terrigenous-siliceous rocks. Here, clearly defined ore-bearing horizons are also traced, characterized by vertical zoning by ore type and degree of metasomatic transformation.

Below is a stratigraphic section of the Western Karazhal iron-manganese deposit (Fig.3), including alternation of limestones, siliceous and carbonate rocks with zones of iron and manganese saturation, demonstrates a similar structure and can be used as a regional stratigraphic analogue. Thus, the presence of stable stratigraphic levels prone to mineralization is confirmed for a number of deposits in Central Kazakhstan [7].

Thus, the stratigraphic confinement of ore bodies to Devonian and Lower Carboniferous deposits of siliceous-carbonate nature, the presence of vertical and lateral zoning zones, as well as the formational stability of ore-bearing horizons form the basis for forecasting new deposits. Stratigraphic control is a key factor in constructing geological models, verifying ore bodies and assessing resources.

Structural features. The tectonic structure of the Kentobe-Togai region is characterized by pronounced dislocation, a complex system of faults of various directions and genesis. The faults here form not only the tectonic framework, but also

determine the spatial architecture of ore bodies, their morphology and localization.

The study area is characterized by a plurality of faults, both regional and local in scale. Active faults with various kinematic characteristics have been recorded in almost every area (Kentobe I, II, III, East Kentobe, Togay I–IV, Sarybulak): shear faults, normal faults, reverse faults, shear activation zones, and tectonic fragmentation zones. In addition to large faults, multiple local fractured zones and tectonic fragmentation zones have been recorded, which are found in borehole cores and near adits. Small lenticular bodies of martite and hematite, sometimes with clay regeneration, are often observed in these zones [8].

This multiplicity of faults leads to the formation of ore bodies that are heterogeneous in thickness and geometry; segmentation of deposits, when one body is broken up into several isolated lenses or stocks; duplication of bodies, especially in cases of parallel faults; the outcrop of ore bodies on the surface along fault zones (for example, Togay I–II); recrystallization of minerals in zones of maximum tectonic activity. In a number of areas, especially in Kentobe III and Togay IV, structures of the "tectonic staircase" type are recorded - a series of parallel small faults that displace a sheet-like deposit down the steps. Under these conditions, ore bodies show a stepped morphology, and the mineralization zone is complicated by secondary dislocations [8].

Ore bodies are morphologically adapted to these structures. Their shape varies from sheet-like - with stable layering and the absence of intense tectonics, lens-shaped - with splitting in bending and compression zones, stock-like and columnar - under the influence of vertical structures, to chaotic and isometric — in zones of intense crushing and skarnoidization. Structural controllability is especially clearly traced in exocontact zones between granitoid intrusions and siliceous-carbonate strata. Here, faults form frames for fluid migration and zones of metasomatic enrichment in iron. It is often along these zones that magnetite and skarnoid bodies are traced, often in combination with garnet-epidote parageneses [9].

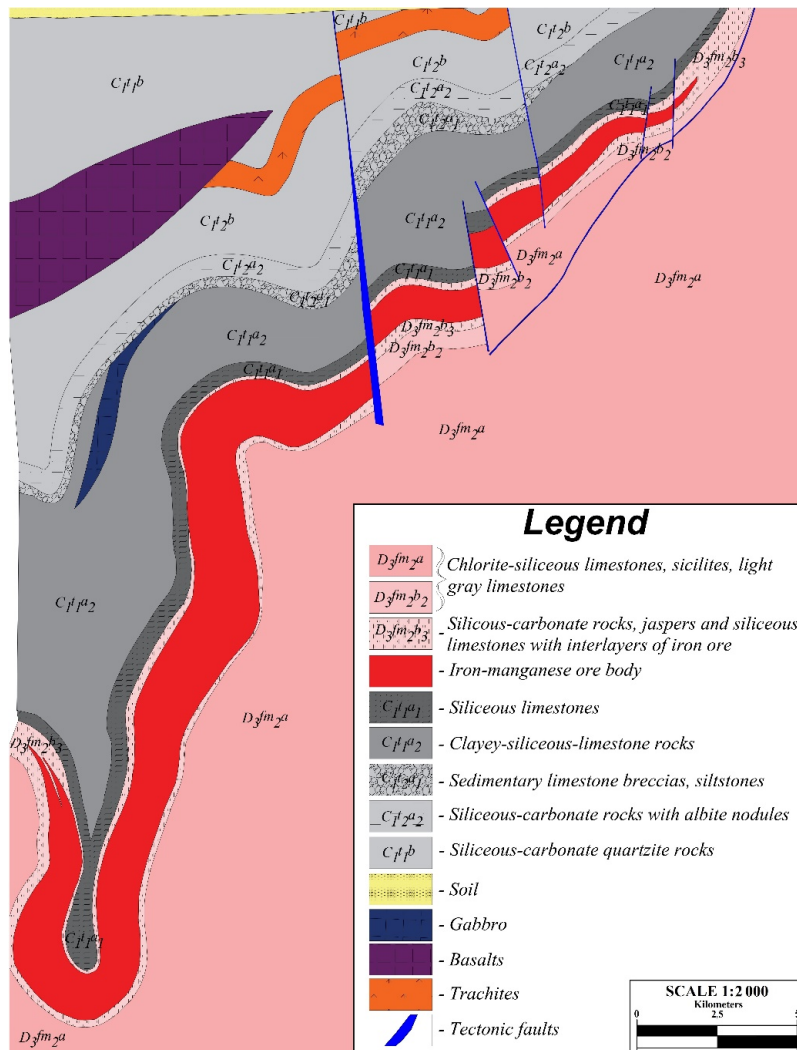


Fig.3 - Stratigraphic section of the Western Karazhal deposit (Ulytau region) with the allocation of ore bodies and tectonic faults. Scale 1:2,000

Fig.4 shows a spatial model reflecting the position of iron ore bodies (blue) and tectonic faults (red) in a southeast-northwest (SE–NW) projection. The model clearly demonstrates that the ore bodies are closely controlled by a system of sublatitudinal and diagonal faults, and in some cases their intersection and displacement are observed, which confirms the active role of structural disturbances in the formation of the morphology of the bodies. This picture corresponds to the concept of a “tectonic staircase” previously described for the Kentobe III area.

Fig.5 illustrates the interaction of ore bodies (blue) with intrusive bodies (yellow), reflected as wireframes based on the 3D geomodel data. The view in the southwest-northeast (SW-NE)

projection allows us to trace how exocontact zones of granitoid intrusion spatially coincide with zones of skarnoid and magnetite mineralization. This confirms the key role of intrusion contacts in the processes of iron enrichment and metasomatic transformation of host rocks. The presence of through intrusive bodies intruding at different levels illustrates the multi-stage nature of tectono-magmatic processes that accompanied ore formation.

The presented three-dimensional models not only visualize the complex spatial structure of the Kentobe deposit ore field, but also serve as a basis for further block modeling and the application of geostatistical interpolation methods, allowing for a quantitative assessment of reserves taking into

account the anisotropy and segmentation of ore bodies.

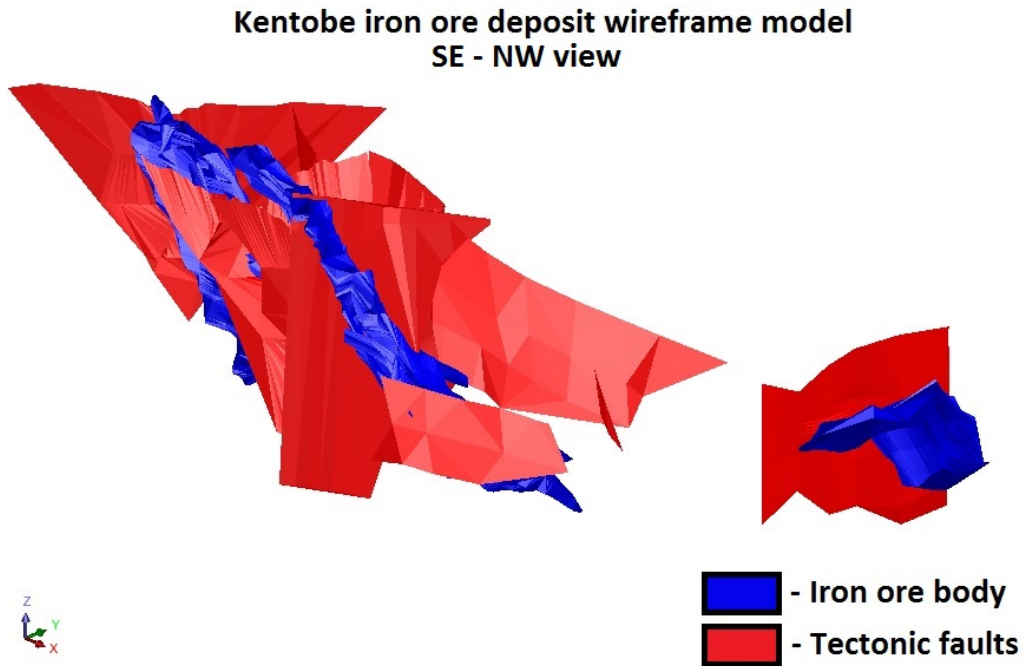


Fig.4 - 3D image of the main faults in the Kentobe (Surpac) field. SE – NW view

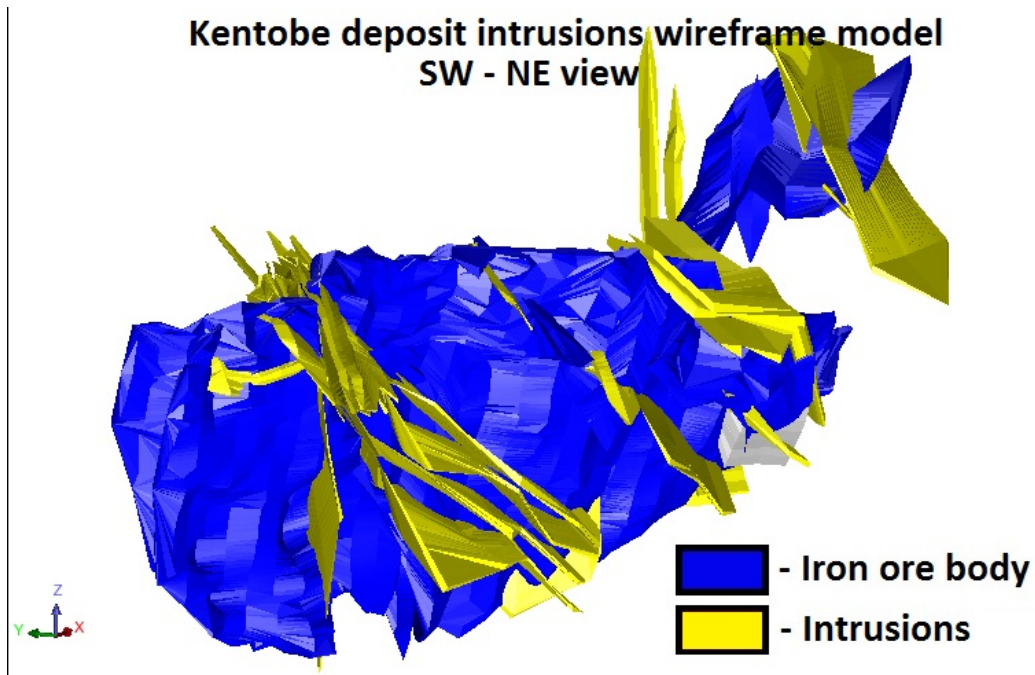


Fig.5 - 3D image of the main intrusions at the Kentobe (Surpac) deposit. SW – NE view

It should be noted that the use of digital methods of geological modeling in conditions of complex tectonics and stratigraphic heterogeneity is justified not only for iron ore deposits. Similar methods were

successfully used by the authors in modeling rare earth element deposits in Eastern Kazakhstan [10], which confirms their universality and applicability for geological objects of various genesis [10, 11].

Comparison of data for all areas of the Kentobe-Togay group allows dividing the region into structural tectonic blocks, each of which has its own system of bodies and structures. Thus, the multiplicity of faults and tectonic disturbances is a determining factor in the spatial distribution, shape and preservation of ore bodies within the siliceous-carbonate formations of Central Kazakhstan. Structural analysis must necessarily precede modeling and resource assessment, especially when constructing block models and selecting interpolation parameters.

The Kentobe-Togay group is a unique platform for constructing geological and block models in conditions of complex stratigraphy and active tectonics. The established confinement of ore bodies to stable stratigraphic horizons and fault zones allows the use of structural 3D interpretation methods (Figures 4, 5) [12, 13].

Results and discussions. The results of the conducted study of the stratigraphic and structural conditions of the iron ore deposits of the Kentobe-Togay group made it possible to form a complete geological and structural picture of the formation and spatial distribution of ore bodies within the siliceous-carbonate formation of Central Kazakhstan. It was established that ore formation in this zone is due to the combined effect of stratigraphic, lithological, tectonic and metasomatic factors, the interrelation of which forms local conditions of iron enrichment. The following key patterns were identified:

- the confinement of ore bodies to Upper Devonian and Lower Carboniferous alternating carbonate-siliceous deposits with high reactivity; the siliceous-carbonate formations of Central Kazakhstan have stable lithological and stratigraphic features favorable for the concentration of iron;

- the influence of contact metamorphism during the introduction of granitoid intrusions, leading to

the formation of hornfels and skarnoid enrichment zones;

- the active role of tectonic faults, which form both fluid migration channels and structural traps and tectonic steps that duplicate and segment ore bodies;

- vertical mineralogical zoning, expressed in the replacement of primary magnetite ores by hematite and martite in oxidation zones, as well as the appearance of skarns and metasomatism zones in the deep parts;

- pronounced parametric heterogeneity of ore bodies: variability in thickness, discontinuity, stepped morphology.

These factors do not act in isolation - they combine to form unique geological systems where mineralization is systematically controlled by stratigraphy and structure. It is this type of deposit that requires a more in-depth approach to interpretation and modeling.

A comparison of the geological conditions of the Kentobe-Togay group with a well-studied industrial object, the Western Karazhal deposit, shows that the described patterns of stratigraphic and structural control of ore occurrences are typical for siliceous-carbonate formations of Central Kazakhstan as a whole. Thus, the results of this study can be used as a basis for developing a methodology for modeling and assessing the resources of stratiform and contact-metamorphosed iron ore deposits in similar geological settings [13, 14].

The use of modern digital technologies, including 3D block modeling, geostatistical methods for estimating grades (kriging, IDW, nearest neighbor method) and fault reconstruction, can significantly increase the reliability of resource estimates and reduce uncertainty with limited drilling density [13, 14].

Areas with the highest data density and better geological knowledge are especially promising for testing and developing such approaches. In these areas, it is possible not only to create more realistic geological and resource models, but also to develop various scenarios for interpolation and reserve assessment, which is critically important given the

limited drilling data and fragmentary geological information.

Conclusions. The comprehensive analysis of stratigraphic and structural features of the Kentobe–Togai group of iron ore deposits has shown that their formation is the result of a complex interplay of stratigraphic, lithological, tectonic, and metasomatic factors. The research established that ore bodies are consistently confined to Upper Devonian and Lower Carboniferous siliceous–carbonate sequences, whose lithological reactivity created favorable conditions for the concentration of iron. The processes of contact metamorphism, triggered by granitoid intrusions, played a decisive role in the formation of hornfels, skarn-like rocks, and localized iron enrichment zones. Tectonic structures proved to be a key controlling factor in ore localization and morphology. Fault systems not only determined the spatial architecture of the deposits but also provided migration channels for ore-forming fluids. As a result, ore bodies often display segmentation, duplication, and stepped morphologies typical of zones with high tectonic activity. Vertical mineralogical zoning was also documented, with primary magnetite ores giving way to hematite–martite assemblages in oxidation zones and to skarnoid enrichment in deeper levels. This multilevel structure highlights the dynamic nature of ore-forming processes.

A significant outcome of the study is the demonstration of parametric heterogeneity in ore bodies: their thickness, shape, and continuity vary considerably depending on stratigraphic

position and structural control. Such heterogeneity requires the application of modern digital geological methods. Three-dimensional geological and structural modeling, block modeling, and geostatistical interpolation allow a more reliable reconstruction of deposit architecture, support resource assessment, and reduce uncertainties associated with limited exploration drilling.

Comparison with the Western Karazhal deposit confirmed that the identified patterns of stratigraphic confinement, tectonic control, and metasomatic transformation are not unique to Kentobe–Togai but represent general trends characteristic of siliceous–carbonate formations of Central Kazakhstan. Therefore, the results of this study can be used as a methodological basis for predicting, modeling, and assessing stratiform and contact-metamorphosed iron ore deposits in analogous geological settings.

In summary, the Kentobe–Togai group provides a natural model for understanding the interplay of stratigraphy, tectonics, and magmatism in the genesis of iron ore mineralization. The integration of field observations, structural analysis, and advanced 3D modeling confirms the universality of the identified patterns and emphasizes the necessity of applying such approaches in regional exploration and resource evaluation. These findings contribute not only to the expansion of the mineral resource base of Kazakhstan but also to the advancement of theoretical concepts of ore-forming systems in complex geodynamic environments.

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Information about authors

Kim V.O.- doctoral student, NJSC "Karaganda Technical University named after Abylkas Saginov", Karaganda, Kazakhstan, e-mail: kim_v@mail.ru;

Cheskidov V. V.- Candidate of Engineering, Sciences, University of Science and Technology MISIS, Moscow, Russian Federation, e-mail: vcheskidov@misis.ru;

Maussymbayeva A. D.- PhD, University of Illinois at Urbana Champaign, Champaign, USA, e-mail: maussymbayevaaliya@gmail.com;

Madisheva R. K. - PhD, Associate Professor, Karaganda Technical University named after Abylkas Saginov, Karaganda, Kazakhstan, e-mail: rimma_kz@mail.ru;

Issatayeva F. M.- PhD, associate professor, Abylkas Nenets Administrative District "Karaganda Technical University named after Abylkas Saginov", Karaganda, Kazakhstan, e-mail: adambekova_farid@mail.ru;

Askarova N. S.- PhD, Karaganda Technical University named after Abylkas Saginov, Karaganda, Kazakhstan, e-mail: srajadinnazym@mail.ru;

Imanbaeva S. B.- PhD, NJSC "Karaganda Technical University named after Abylkas Saginov", Karaganda, Kazakhstan, e-mail: svetakaz77@mail.ru.

Сведения об авторах

Ким В.О.- докторант, НАО «Карагандинский технический университет им. Абылкаса Сагинова», Караганда, Казахстан, e-mail: kim_v@mail.ru;

Ческидов В.В.- кандидат технических наук, НИТУ «МИСиС», Москва, Российская Федерация, e-mail: vcheskidov@misis.ru;

Маусымбаева А. Д.- PhD, университет Иллинойса в Урбана Шампейн, Шампейн, Иллинойс США, доктор философии, e-mail: maussymbayevaaliya@gmail.com;

Мадишева Р.К.- PhD, ассоциированный профессор, НАО «Карагандинский технический университет им. Абылкаса

Сагинова», Караганда, Казахстан, e-mail: gimma_kz@mail.ru;

Исатаева Ф.М.- PhD, ассоциированный профессор, НАО «Карагандинский технический университет им. Абылкаса Сагинова», Караганда, Казахстан, e-mail: adambekova_farid@mail.ru;

Аскарова Н.С. – PhD, НАО «Карагандинский технический университет им. Абылкаса Сагинова», Караганда, Казахстан, e-mail: srajadin-nazym@mail.ru;

Иманбаева С.Б.- PhD, НАО «Карагандинский технический университет им. Абылкаса Сагинова», Караганда, Казахстан, E-mail: svetakaz77@mail.ru.