

ISSN 2518-170X (Online)

ISSN 2224-5278 (Print)

**NEWS OF THE NATIONAL ACADEMY
OF SCIENCES OF THE REPUBLIC
OF KAZAKHSTAN, SERIES OF
GEOLOGY AND TECHNICAL SCIENCES**

№3

2026

ISSN 2518-170X (Online)

ISSN 2224-5278 (Print)



N E W S
OF THE NATIONAL ACADEMY OF SCIENCES
OF THE REPUBLIC OF KAZAKHSTAN,
SERIES OF GEOLOGY AND TECHNICAL
SCIENCES

3 (477)
JUNE – JULY 2026

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, 2026

The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

The journal is also included in the Emerging Sources Citation Index (ESCI) of the Web of Science platform (Clarivate Analytics, since 2018).

Indexing in ESCI confirms the journal's compliance with international standards of scientific peer review and editorial ethics and is considered by Clarivate Analytics as part of the evaluation process for potential inclusion in the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI).

Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«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.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

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).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.

ISSN 2518-170X (Online),

ISSN 2224-5278 (Print)

Owner: «Central Asian Academic Research Center» LLP (Almaty).

The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Communications of the Republic of Kazakhstan № KZ50VPY00121155, issued on 05.06.2025
Thematic scope: *geology, hydrogeology, geography, mining and chemical technologies of oil, gas and metals*
Periodicity: 6 times a year.

<http://www.geology-technical.kz/index.php/en/>

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.

ISSN 2518-170X (Online),

ISSN 2224-5278 (Print)

Меншіктеуші: «Орталық Азия академиялық ғылыми орталығы» ЖШС (Алматы қ.).

Қазақстан Республикасының Ақпарат және коммуникациялар министрлігінің Ақпарат комитетінде 05.06.2025 ж. берілген № KZ50VPY00121155 мерзімдік басылым тіркеуіне қойылу туралы куәлік. Тақырыптық бағыты: *геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.

ISSN 2518-170X (Online),

ISSN 2224-5278 (Print)

Собственник: ТОО «Центрально-Азиатский академический научный центр» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и коммуникаций и Республики Казахстан № KZ50VPY00121155, выданное 05.06.2025 г.

Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*

Периодичность: 6 раз в год.

<http://www.geolog-technical.kz/index.php/en/>

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NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC
OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224-5278
Volume 3.
Number 477 (2026), 410–424

<https://doi.org/10.32014/2026.2518-170X.661>

UDC: 553.3/4.38.49.15

IRSTI: 38.49.17

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GOLD-FORMING PROCESSES AND PREDICTIVE CRITERIA OF GOLD–CARBONACEOUS–SULFIDE MINERALIZATION AT THE BAKYRSHIK DEPOSIT (EASTERN KAZAKHSTAN)

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Abstract. Relevance. Gold–carbonaceous–sulfide deposits are among the most economically significant types of gold mineralization and constitute an important part of the mineral resource base of Kazakhstan. Under conditions of depletion of easily discoverable gold deposits, increasing importance is attached to studies focused on ore-forming processes, ore-controlling factors, and predictive geological criteria that can improve the efficiency of exploration for concealed and deep-seated mineralization. The Bakyrshik deposit, located within the West Kalba gold belt of Eastern Kazakhstan, is one of the largest and most representative deposits of this type and serves as an important object for studying the genesis, localization patterns, and evolution of gold mineralization

within carbonaceous–terrigenous complexes. *Objective.* The aim of the study is to investigate gold-forming processes and substantiate predictive geological criteria for gold–carbonaceous–sulfide mineralization using the Bakyrshik deposit as a case study. *Methods.* The study is based on the integrated analysis of field geological observations, mineralogical and microscopic investigations, geochemical data, as well as published and archival materials. Particular attention was paid to lithological, structural–tectonic, mineralogical, and geochemical factors controlling ore localization. The role of carbonaceous matter, sulfide mineralization, hydrothermal–metasomatic processes, and geochemical barriers in the accumulation and redistribution of gold was analyzed. Modern concepts concerning the remobilization and redeposition of gold within carbonaceous–terrigenous complexes, as well as data on the structural–lithological control of mineralization, were used to interpret ore-forming conditions. *Results.* It was established that reducing geochemical barriers associated with carbonaceous–terrigenous sequences and tectonic disturbance zones played a decisive role in gold concentration. Carbonaceous matter was shown to perform simultaneously as a sorbent and reducing agent, ensuring the fixation and accumulation of mobile gold forms. A staged evolution of gold mineralization was identified, including the transformation of ionic, colloidal, and nano-sized gold forms into native gold. The main predictive criteria include confinement to carbonaceous complexes, structural control by faults and thrust zones, magmatic influence, development of pyrite–arsenopyrite associations, and elevated concentrations of pathfinder elements. Based on the obtained data, a predictive geological model of gold–carbonaceous–sulfide mineralization for the Bakyrshik deposit was proposed. *Conclusions.* The identified predictive criteria and the proposed geological model can be applied in the forecasting, exploration, and assessment of analogous deposits within the gold-bearing belts of Kazakhstan and adjacent territories, as well as in determining перспективные directions for further geological exploration activities.

Keywords: akyrshik deposit; gold–carbonaceous–sulfide mineralization; gold-forming processes; carbonaceous matter; geochemical barriers; predictive model; Eastern Kazakhstan

Acknowledgement: The article was prepared within the framework of the grant financing project of the Ministry of Science and Higher Education of the Republic of Kazakhstan «Scientific substantiation of the expansion and replenishment of mineral resources of priority and critical minerals as the basis for the innovative development of Kazakhstan» for 2024–2026. (IRN: BR27199165).

For citations: Zholtayev G.Zh., Umarbekova Z.T., Mashrapova M.A., Gadeev R.R., Amanbaev R.A. Gold-Forming Processes and Predictive Criteria of Gold–Carbonaceous–Sulfide Mineralization at the Bakyrshik Deposit (Eastern Kazakhstan). *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences.* 2026. No.3. Pp. 410–424. DOI: <https://doi.org/10.32014/2026.2518-170X.661>

©Жолтаев Г.Ж.¹, Умарбекова З.Т.¹, Машрапова М.А.^{1*}, Гадеев Р.Р.¹,
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БАҚЫРШЫҚ КЕН ОРНЫНДАҒЫ (ШЫҒЫС ҚАЗАҚСТАН) АЛТЫН ТҮЗІЛУ ПРОЦЕСТЕРІ ЖӘНЕ АЛТЫН-КӨМІРТЕК- СУЛЬФИДТІ МИНЕРАЛДАНУДЫҢ БОЛЖАУ КРИТЕРИЙЛЕРІ

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Аннотация. *Өзектілігі.* Алтын-көміртекті-сульфидті кен орындары алтын кенденуінің экономикалық тұрғыдан аса маңызды типтерінің бірі болып табылады және Қазақстанның минералдық-шикізат базасының маңызды бөлігін құрайды. Жеңіл анықталатын алтын кен орындарының сарқылуы жағдайында жасырын және терең орналасқан кенденуді іздеу тиімділігін арттыруға мүмкіндік беретін кен түзілу процестерін, кенді бақылаушы факторларды және болжамдық геологиялық критерийлерді зерттеуге ерекше назар аударылуда. Шығыс Қазақстандағы Батыс Қалба алтын белдеуі шегінде орналасқан Бақыршық кен орны осы типтегі ең ірі әрі ең көрнекті нысандардың бірі болып табылады және көміртекті-терригендік кешендердегі алтынды минералданудың генезисін, орналасу заңдылықтарын және эволюциясын зерттеудің маңызды объектісі саналады. *Зерттеудің мақсаты* – Бақыршық кен орны мысалында алтын түзілу процестерін зерттеу және алтын-көміртекті-сульфидті кенденудің болжамдық геологиялық критерийлерін негіздеу. *Әдістері.* Зерттеу далалық геологиялық бақылауларды, минералогиялық және микроскопиялық зерттеулерді, геохимиялық мәліметтерді, сондай-ақ жарияланған және қор материалдарын кешенді талдауға негізделген. Кенденудің орналасуын бақылайтын литологиялық, құрылымдық-тектоникалық, минералогиялық және геохимиялық факторларға ерекше назар аударылды. Алтынның жиналуы мен қайта таралуындағы көміртекті

заттың, сульфидті минералданудың, гидротермалдық-метасоматикалық процестердің және геохимиялық тосқауылдардың рөлі талданды. Кен түзілу жағдайларын түсіндіру үшін көміртекті-терригендік кешендердегі алтынның ремобилизациясы мен қайта шөгуі туралы заманауи ғылыми көзқарастар, сондай-ақ минералданудың құрылымдық-литологиялық бақылауы жөніндегі деректер пайдаланылды. *Нәтижелері.* Алтынның шоғырлануында көміртекті-терригендік қабаттармен және тектоникалық бұзылу аймақтарымен байланысты тотықсыздандырғыш геохимиялық тосқауылдардың шешуші рөл атқаратыны анықталды. Көміртекті заттың сорбент және тотықсыздандырғыш қызметін қатар атқара отырып, алтынның қозғалмалы формаларын бекітіп, олардың жиналуын қамтамасыз ететіні көрсетілді. Алтын минералдануының иондық, коллоидтық және наноөлшемді формалардан табиғи алтынға дейінгі сатылы эволюциясы анықталды. Негізгі болжамдық критерийлерге көміртекті кешендерге тән шоғырлану, жарылымдар мен ығысу аймақтарының құрылымдық бақылауы, магмалық әсер, пирит-арсенопирит ассоциацияларының дамуы және индикатор-элементтердің жоғары мөлшері жатқызылды. Алынған мәліметтер негізінде Бақыршық кен орнының алтын-көміртекті-сульфидті кенденуінің болжамдық геологиялық моделі ұсынылды. *Қорытындылар.* Анықталған болжамдық критерийлер мен ұсынылған геологиялық модель Қазақстанның және оған шектес аумақтардың алтын белдеулері шегіндегі ұқсас кен орындарын болжау, іздеу және бағалау жұмыстарында, сондай-ақ болашақ геологиялық барлау бағыттарын анықтауда қолданылуы мүмкін.

Түйін сөздер: Бақыршық кен орны; алтын-көміртекті-сульфидті минералдану; алтын түзу процестері; көміртекті зат; геохимиялық кедергілер; болжам моделі; Шығыс Қазақстан

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ЗОЛОТООБРАЗУЮЩИЕ ПРОЦЕССЫ И ПРОГНОЗНЫЕ КРИТЕРИИ ЗОЛОТО-УГЛЕРОДИСТО-СУЛЬФИДНОГО ОРУДЕНЕНИЯ МЕСТОРОЖДЕНИЯ БАКЫРШИК (ВОСТОЧНЫЙ КАЗАХСТАН)

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Аннотация. *Актуальность.* Золото-углеродисто-сульфидные месторождения относятся к числу наиболее экономически значимых типов золотого оруденения и составляют важную часть минерально-сырьевой базы Казахстана. В условиях истощения легкообнаруживаемых золоторудных объектов особую актуальность приобретают исследования, направленные на изучение рудообразующих процессов, рудоконтролирующих факторов и прогнозных геологических критериев, позволяющих повысить эффективность поисков скрытого и глубинного оруденения. Месторождение Бакыршик, расположенное в пределах Западно-Калбинского золоторудного пояса Восточного Казахстана, является одним из крупнейших и наиболее представительных объектов данного типа и представляет собой важный объект для изучения генезиса, закономерностей локализации и эволюции золотоносной минерализации в углеродисто-терригенных комплексах. *Цель.* Изучить золотообразующие процессы и обосновать прогнозные геологические критерии золото-углеродисто-сульфидного оруденения на примере месторождения Бакыршик. *Методы.* Исследование основано на комплексном анализе полевых геологических наблюдений, минералогических и микроскопических исследований, геохимических данных, а также опубликованных и фондовых материалов. Особое внимание уделено литологическим, структурно-тектоническим, минералогическим и геохимическим факторам, контролирующим локализацию оруденения. Проанализирована роль углеродистого вещества, сульфидной минерализации, гидротермально-метасоматических процессов и геохимических барьеров в накоплении и перераспределении золота. Для интерпретации условий рудообразования использованы современные представления о процессах ремобилизации и переотложения золота в углеродисто-терригенных комплексах, а также данные о структурно-литологическом контроле минерализации. *Результаты и выводы.* Установлено, что решающую роль в концентрации золота играли восстановительные геохимические барьеры, связанные с углеродисто-терригенными толщами и зонами тектонических нарушений. Показано, что углеродистое вещество одновременно выполняло функции сорбента и восстановителя, обеспечивая фиксацию и накопление подвижных форм золота. Выявлена стадийная эволюция золотоносной минерализации, включающая преобразование ионных, коллоидных и наноформ золота в самородную форму. К основным прогнозным критериям отнесены приуроченность к углеродистым комплексам, структурный контроль разломами и зонами надвигов, магматическое воздействие, развитие пирит-арсе-

нопиритовых ассоциаций и повышенные содержания элементов-индикаторов. На основе полученных данных предложена прогнозная геологическая модель золото-углеродисто-сульфидного оруденения месторождения Бакыршик. Выявленные прогнозные критерии и предложенная геологическая модель могут быть использованы при прогнозировании, поисках и оценке месторождений аналогичного типа в пределах золоторудных поясов Казахстана и сопредельных территорий, а также при выборе перспективных направлений дальнейших геологоразведочных работ.

Ключевые слова: месторождение Бакыршик; золото-углеродисто-сульфидное оруденение; золотообразующие процессы; углеродистое вещество; геохимические барьеры; прогнозная модель; Восточный Казахстан

Introduction. Gold–carbonaceous–sulfide deposits are among the most economically significant types of gold mineralization and play an important role in the formation of the mineral resource base of the Republic of Kazakhstan. Under conditions of depletion of easily discoverable deposits, studies aimed at an in-depth investigation of gold-forming processes, identification of ore-controlling factors, and development of predictive geological models that enhance the efficiency of exploration activities become particularly relevant.

One of the most representative objects of this type is the Bakyrshik deposit, located within the West Kalba gold belt of Eastern Kazakhstan. The exceptional scale of mineralization, its confinement to carbonaceous terrigenous sequences, and the complex multistage history of ore formation allow Bakyrshik to be regarded as a reference deposit for the study of the gold–carbonaceous–sulfide deposit type.

Despite the long history of investigation of the deposit, issues related to the genesis of gold, the role of carbonaceous matter, mechanisms of noble metal precipitation, and the significance of geochemical barriers remain debated. This necessitates a comprehensive analysis of geological, mineralogical, and geochemical data in order to synthesize current concepts of gold-forming processes and to apply them practically in the prediction of analogous deposits.

The aim of this article is to analyze gold-forming processes and to substantiate predictive geological criteria for gold–carbonaceous–sulfide mineralization using the Bakyrshik deposit as a case study, with the development of a generalized predictive model applicable to the exploration of this deposit type within Kazakhstan.

Geological setting. The Bakyrshik deposit is located in the central part of the West Kalba gold belt, which is characterized by a high concentration of gold deposits of various scales. The geological structure of the area is controlled by the development of Carboniferous carbonaceous terrigenous complexes, which played a key role in the formation of economically significant gold mineralization (Figure 1).

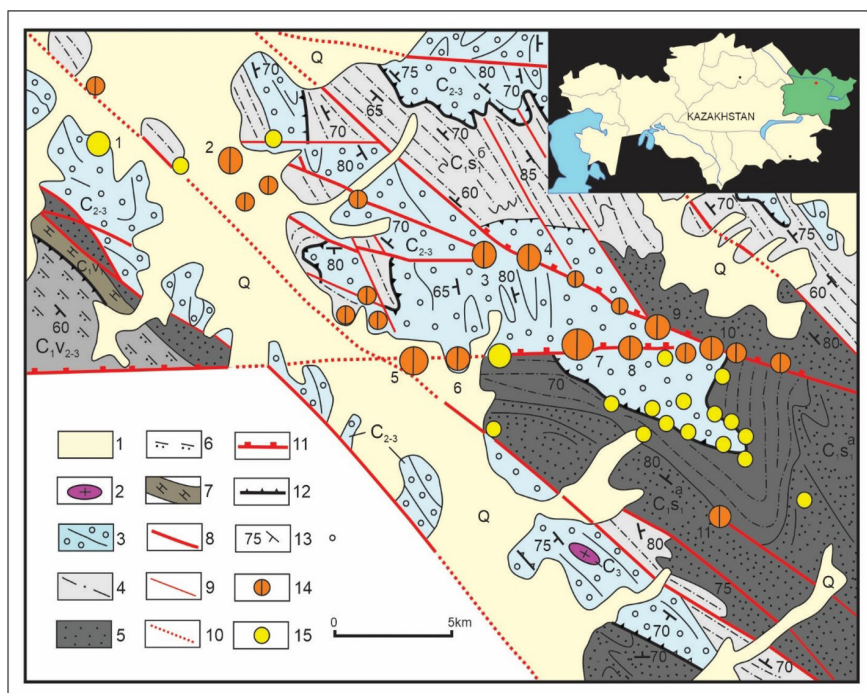


Figure 1. Geological map of the Bakyrshik ore field (Zimanovskaya, 2014).

1 – Quaternary deposits; 2–7 – geological formations: 2 – plagiogranite–granodiorite formation, C_3 ; 3 – molasse limnic carbonaceous formation, C_{2-3} ; 4, 5 – greywacke siltstone–sandstone formation, C_{1s} (4 – upper sandstone–siltstone subformation; 5 – lower sandstone subformation); 6 – flyschoid carbonaceous–calcareous–terrigenous formation, C_{1v2-3} ; 7 – limestone–sandstone–siltstone formation, C_{1v1} ; 8–11 – faults (8 – deep-seated; 9 – minor faults; 10 – faults concealed beneath unconsolidated deposits; 11 – ore-controlling faults); 12 – thrust faults; 13 – bedding elements; 14–15 – ore formations (14 – gold–arsenic–carbonaceous; 15 – gold–quartz). Deposits: 1 – Espe; 2 – Kostobe; 3 – Dalnyi I; 4 – Dalnyi; 5 – Bolshevik; 6 – Chelobay; 7 – Bakyrshik; 8 – Glubokiy Log; 9, 10 – Promezhutochnoe; 11 – Bizhan.

The stratigraphic section is dominated by carbonaceous terrigenous deposits, represented by siltstones, sandstones, argillites, and their carbonaceous varieties enriched in organic matter. These sequences are regarded as a lithogeochemical framework that facilitated the accumulation and subsequent concentration of gold during ore-forming processes (Zimanovskaya, 2014; Bespaev and Parilov, 2018).

Magmatic rocks within the deposit are represented by intrusions of the Kunush gabbro–diorite–granodiorite complex, as well as dike bodies of various compositions. Their emplacement was accompanied by thermal and fluid воздействие on the host rocks, which promoted the activation of hydrothermal–metasomatic processes and the redistribution of ore material (Zenkova, 1975).

The tectonic framework of the deposit is characterized by the development of thrust and strike-slip structures, zones of intense deformation, pervasive fracturing, and schistosity of the rocks. Ore bodies are generally confined to zones

of tectonic disturbances and occur subparallel to the main structural elements. This structural setting determined the formation of laterally extensive mineralized zones of considerable thickness and played a decisive role in the localization of gold mineralization (Starova, 1980).

The structural control and spatial distribution of ore bodies at the Bakyrshik deposit are shown in Figure 2.

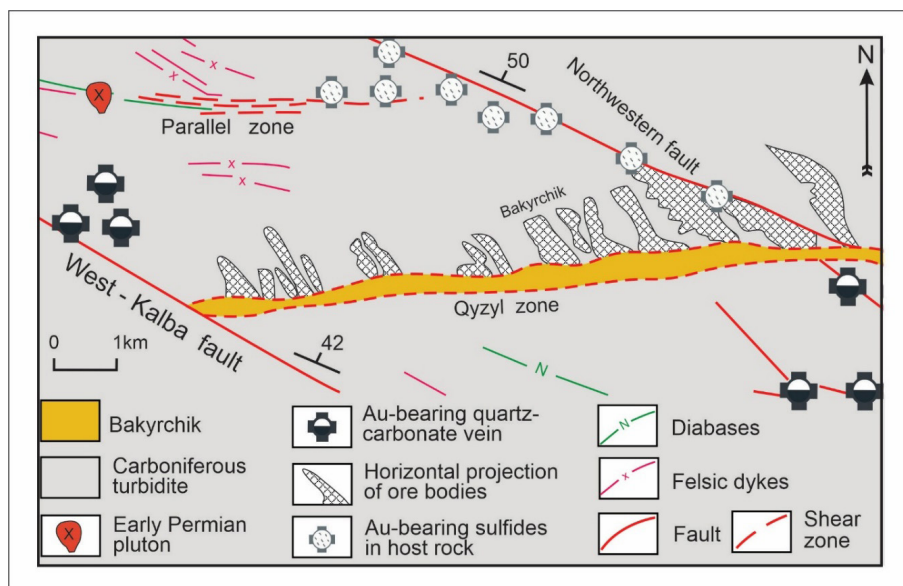


Figure 2. Ore-controlling structural elements and distribution of ore bodies at the Bakyrshik deposit.

The combination of stratigraphic, lithological, magmatic, and tectonic factors led to the formation of the Bakyrshik deposit as a large gold–carbonaceous–sulfide system with pronounced polychronous and multistage ore-forming processes, making it a key object for the development of predictive models for this type of mineralization.

Materials and Methods. The study is based on the integrated analysis of field geological observations, mineralogical and petrographic investigations, microscopic studies, geochemical data, published scientific literature, and archival geological materials related to the Bakyrshik deposit and the West Kalba gold belt.

Structural–tectonic, lithological, mineralogical, and geochemical factors controlling the localization of gold mineralization were analyzed. Particular attention was paid to the distribution of carbonaceous matter, sulfide mineralization, hydrothermal–metasomatic alterations, and geochemical barriers associated with gold concentration.

Comparative analysis of published geological models and ore-forming concepts for gold–carbonaceous–sulfide deposits was carried out. Interpretation of gold-

forming processes was based on modern concepts of remobilization, redistribution, and precipitation of gold within carbonaceous–terrigenous complexes under tectono-metamorphic and hydrothermal conditions.

Results and Discussion. *Gold-forming processes.* The formation of gold–carbonaceous–sulfide mineralization at the Bakyrshik deposit is associated with the multistage and polychronous development of ore-forming processes, which occurred under the close interaction of sedimentary, tectonic, magmatic, and hydrothermal–metasomatic factors (Marchenko, 1980). A leading role in gold concentration at various stages of ore formation was played by the carbonaceous matter of the carbonaceous–terrigenous sequences, which acted as an effective geochemical accumulator and reductive barrier.

At the early stages of deposit formation, gold was predominantly present in a dispersed state and was associated with sedimentary and diagenetic processes within the carbonaceous sequences (Zhautikov, 1983; Umarbekova et al., 2017). Organic matter facilitated the fixation of mobile gold forms through sorption and complexation mechanisms, creating conditions for the subsequent redistribution and concentration of the metal.

During subsequent tectono-metamorphic and magmatic events, fluid flow was activated, leading to the redistribution of previously accumulated gold. Increases in temperature and pressure, as well as the influence of hydrothermal solutions, resulted in the mobilization of gold and its reprecipitation in zones of structural disturbances and enhanced rock permeability. At this stage, a characteristic pyrite–arsenopyrite sulfide association developed, closely linked to the concentration of the noble metal (Marchenko, 2007).

Gold in the deposit occurs in various forms—from fine-grained inclusions in sulfides and carbonaceous matter to native gold, reflecting the evolution of physico-chemical conditions during ore formation. The progressive transformation of ionic and colloidal gold forms into native gold indicates the staged nature of the process and the changes in redox conditions within the ore-bearing system.

Tectonic zones played a particularly important role in the gold-forming processes at the Bakyrshik deposit, acting as channels for the migration of ore-bearing fluids and areas of fluid discharge. These zones provided favorable conditions for the interaction of hydrothermal solutions with carbonaceous rocks and sulfide mineralization, promoting intense gold precipitation (Narseev et al., 2001).

Thus, gold-forming processes at the Bakyrshik deposit are characterized by a combination of sedimentary–diagenetic, tectono-metamorphic, and hydrothermal stages, each contributing to the formation of economically significant mineralization. This multistage model of gold formation forms the basis for identifying predictive geological criteria and developing a generalized predictive model for gold–carbonaceous–sulfide type deposits.

Geochemical barriers and gold evolution. A key role in the formation of economically significant gold concentrations at the Bakyrshik deposit was played by geochemical barriers, which controlled the processes of precipitation

and redistribution of the noble metal at various stages of ore formation. Their development was determined by a combination of lithological, structural, and physicochemical factors, which defined the reducing nature of the ore-bearing environment.

The most significant were reducing geochemical barriers associated with carbonaceous terrigenous sequences enriched in organic matter. Interaction between ore-bearing fluids and carbonaceous rocks caused abrupt changes in the redox potential of the environment, facilitating the breakdown of gold complexes and the precipitation of gold in the solid phase. Carbonaceous matter performed a dual function—as a reductant and a sorbent, ensuring both the fixation of mobile gold forms and their subsequent concentration (Zairi and Glukhov, 1987).

Structural–tectonic barriers also played an important role in gold evolution. These were associated with thrust zones, faults, and areas of intense fracturing, acting both as migration channels for hydrothermal fluids and as discharge zones, where abrupt changes in fluid physicochemical parameters (temperature, pressure, composition) created favorable conditions for gold and sulfide precipitation.

The evolution of gold occurrence forms reflects the multistage nature of the ore-forming process. At early stages, gold was mainly present in fine-grained and “hidden” forms, associated with carbonaceous matter and sulfide minerals. Later, as thermodynamic conditions changed, gold progressively coarsened and transformed into native gold, leading to the formation of economically significant ore concentrations.

An additional factor enhancing the effectiveness of geochemical barriers was magmatic influence, which increased temperature and activated hydrothermal processes. Magmatic fluids facilitated the remobilization of previously accumulated gold and its reprecipitation in zones with the most favorable geochemical conditions, resulting in a complex spatiotemporal zonation of mineralization (Umarbekova et al., 2021).

Thus, geochemical barriers at the Bakyrshik deposit functioned as a dynamic system operating throughout multiple stages of ore formation. The sequential evolution of gold—from mobile forms to native gold—determined the formation of highly productive gold–carbonaceous–sulfide ore bodies and served as the basis for identifying predictive geological criteria and constructing a predictive model of the deposit.

Based on the formation and transformation of geochemical barriers, as well as the nature of fluid sources and ore-deposition conditions, three main stages are distinguished in the gold-bearing process at the Bakyrshik deposit (Figure 3):

Stage I – Introduction of gold by juvenile fluids, deposition on the floor of a shallow basin, diagenetic transformation of sediments, and formation of gold-bearing carbonaceous–pelitic rhythmites.

Stage II – Remobilization of syngenetic gold in tectono-metamorphic zones of rock cleavage and deposition on reducing geochemical barriers in areas where metamorphic fluid flows of different directions merged.

Stage III – Remobilization and redeposition of gold at geochemical barriers in thermal fields of dikes and intrusions of the plagiogranite–granodiorite (C₃–P₁) and gabbro–monzonite–syenite–granite (T₁) complexes (Umarbekova et al., 2021).

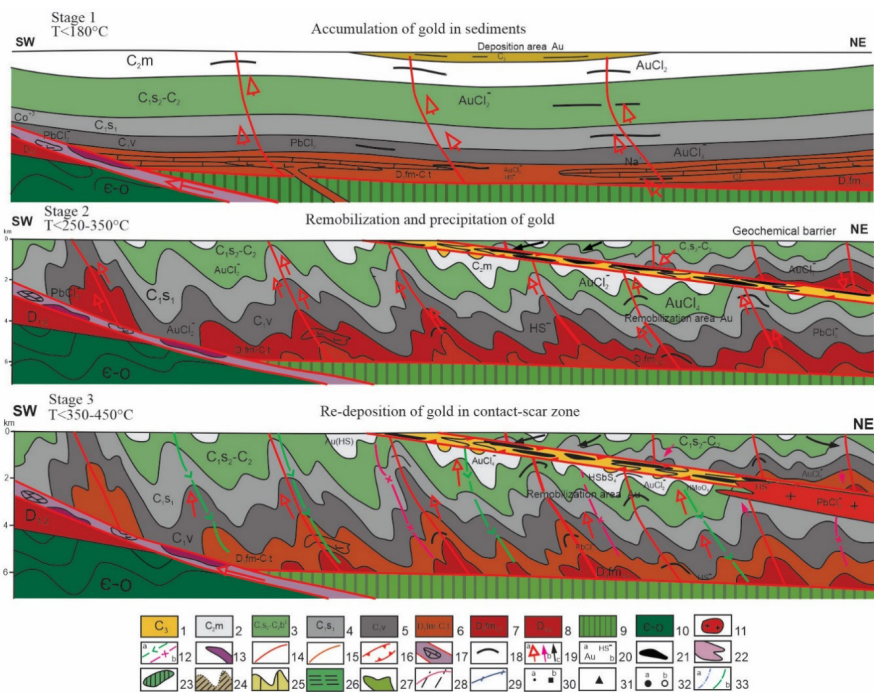


Figure 3. Diagram of gold-forming processes and the functioning of geochemical barriers at the Bakyrshik deposit.

1 – Bakyrshik black shale sequence, C₃; 2 – Bukon conglomerate–sandstone suite, C_{2m}; 3 – Siltstone–sandstone sequence, C_{1s2}–C_{2b}; 4 – Aganakht siltstone–sandstone suite, C_{1s2}; 5 – Opanov argillite–limestone suite, C_{1v}; 6 – Karabay basalt–siliceous–limestone suite, D_{3fm2}–C_{1t}; 7 – Siltstone–pelite deposits, D_{3fm1}–2; 8 – Andesite–basaltic terrigenous deposits; 9 – Oceanic-type basement; 10 – Andesite–basalt–siliceous–terrigenous formations, C₁–O₂; 11 – Plagiogranite–granodiorite intrusions, C₃–P₁; 12 – Sub-alkaline granite–porphyry and monzonite–porphyry dikes (a), diabase and diorite porphyrites (b) of the Semetau (T₁) and Kunush (C₃–P₁) intrusive complexes; 13 – Ultrabasic rocks; 14 – Faults; 15 – Folded viscous fractures; 16 – Kyzyllov thrust zone; 17 – Serpentine lithomelange; 18 – Gold-bearing carbonaceous–pelite–siltstone horizons with syngenetic gold–pyrite–arsenopyrite mineralization; 19 – Directions of juvenile fluid flows (a), metamorphic solutions (b), and meteoric waters (c); 20 – Ore-forming components remobilized during tectono-metamorphic transformation of rocks (a) and introduced by juvenile fluids (b); 21 – Gold ore deposits; 22–27 – Ore-adjacent metasomatic halos: 22 – Intense quartz–sericite alteration; 23 – Albite, chlorite, and carbonate alteration; 24 – Ankerite–quartz veins; 25 – Albite and weak sericitization; 26 – Shungite–sericite metasomatites; 27 – Sideritization of sandstones; 28–29 – Lead isotope ratio diagrams: 28 – Single-stage development model; 29 – Plumbotectonics; 30–31 – Lead isotopes: 30 – O.G. Koshevoy data for ores (a) and syngenetic mineralization (b); 31 – Generalized data by N.G. Syromyatnikov; 32 – Average horizon values of sulfur isotope composition of pyrites (a) and arsenopyrites (b); 33 – Trends in the distribution of $\delta^{34}\text{S}$ values of pyrites (a) and arsenopyrites (b) with ore deposit depth.

Predictive geological criteria for gold–carbonaceous–sulfide mineralization at the Bakyrshik deposit. The identified features of the geological structure, gold-forming processes, and functioning of geochemical barriers at the Bakyrshik deposit made it possible to formulate a system of predictive geological criteria for gold–carbonaceous–sulfide mineralization, which have practical significance for the exploration and assessment of analogous deposits (Table 1).

Among the primary stratigraphic–lithological criteria is the confinement of gold mineralization to Carboniferous carbonaceous–terrigenous sequences enriched in organic matter. The presence of high-carbon horizons, interlayers of black shales, carbonaceous siltstones, and argillites is considered a critical condition for the formation of reducing geochemical barriers that promote the accumulation and precipitation of gold (Lyubetsky, 1984). Zones of abrupt lithological variability, reflecting rhythmic sedimentation and enhanced rock permeability, are of particular predictive importance.

Table 1. Predictive geological criteria for gold–carbonaceous–sulfide mineralization at the Bakyrshik deposit.

Group of criteria	Characteristic	Predictive significance
Stratigraphic	Confinement of mineralization to Carboniferous carbonaceous–terrigenous sequences	Identification of prospective stratigraphic levels for gold mineralization localization
	Presence of high-carbon horizons (black shales, carbonaceous siltstones, argillites)	Formation of reducing geochemical barriers promoting gold concentration
Lithological	Rhythmic alternation of terrigenous rocks of varying composition	Increased permeability and favorable conditions for migration of ore-bearing fluids
	Presence of carbonaceous matter with varying degrees of metamorphism	Sorption and accumulation of mobile gold forms
Structural–tectonic	Zones of thrusts, faults, and shear structures	Channels for migration and discharge of hydrothermal fluids
	Nodes of fault intersection	Most favorable sites for ore body localization
	Intense schistosity and rock fracturing	Improvement of filtration properties of ore-hosting sequences
Magmatic	Presence of intrusive and dike bodies	Source of heat and fluids, activation of ore-forming processes
	Contact zones of intrusions	Areas of superimposed hydrothermal–metasomatic alteration
Mineralogical	Pyrite–arsenopyrite sulfide association	Indicator of gold–carbonaceous–sulfide type mineralization
	Presence of “hidden” gold in sulfides and carbonaceous matter	Sign of early ore-forming stages and potential productivity
Geochemical	Elevated contents of pathfinder elements (As, Sb, Hg, Ni, Co, etc.)	Identification of ore-bearing zones and dispersion halos
	Reducing character of the geochemical environment	Favorable conditions for gold precipitation

Physico-chemical	Changes in redox potential of the environment	Deposition of gold from mobile forms
	Evolution of gold occurrence forms from dispersed to native	Formation of industrially significant concentrations
Integrated Predictive Features	Combination of carbonaceous sequences, fault zones, and magmatic influence	Most prospective areas for exploration and resource assessment

Structural–tectonic criteria are defined by the localization of ore bodies in zones of thrusts, faults, and shear zones, as well as areas of intense schistosity, fracturing, and tectonic brecciation. Intersections of faults with varying orientations, zones of deformation, and cleavage–mylonite structures create favorable conditions for migration and discharge of ore-bearing fluids, and should be considered priority targets for exploration. The spatial relationship of ore bodies with subparallel bedding of the host sequences is a characteristic feature of gold–carbonaceous–sulfide mineralization.

Among magmatic criteria is the presence of intrusive and subvolcanic bodies that exerted thermal and fluid influence on carbonaceous–terrigenous complexes. Magmatic pulses facilitated the activation of hydrothermal processes, remobilization of previously accumulated gold, and its reprecipitation in zones with favorable geochemical conditions. Contact zones of intrusions and areas of superimposed metasomatic alteration are of particular predictive value.

Mineralogical–geochemical criteria include the development of pyrite–arsenopyrite associations, the presence of carbonaceous matter of varying degrees of order, and elevated contents of pathfinder elements (As, Sb, Hg, Ni, Co, etc.). Forms of gold occurrence—from fine-grained and “hidden” forms to native gold—reflect the staged nature of ore formation and can be used to evaluate the productivity of ore zones. Gold assay values are also important as indicators of the physico-chemical conditions of gold precipitation.

The synthesis of these criteria made it possible to propose a predictive geological model of gold–carbonaceous–sulfide mineralization at the Bakyrshik deposit, based on the multistage evolution of the ore-forming system. Within the model, stages are distinguished, including primary accumulation of gold in carbonaceous sediments, subsequent remobilization under tectono-magmatic influence, and concentration of gold on reducing geochemical barriers, resulting in the formation of economically significant ore bodies (Zholtayev, 2025).

The proposed model can be applied in the forecasting and exploration of analogous deposits within the gold-bearing belts of Kazakhstan, as well as in the assessment of previously known but insufficiently studied deposits associated with carbonaceous–terrigenous complexes.

Conclusion. The Bakyrshik deposit is a reference example of gold–carbonaceous–sulfide mineralization, the formation of which is controlled by the combination of carbonaceous–terrigenous sequences, tectonic activity, and hydrothermal–metasomatic processes.

Gold mineralization at the deposit is multistage and polychronous, including stages of primary gold accumulation in carbonaceous sediments, its remobilization under tectono-magmatic influence, and subsequent concentration on reducing geochemical barriers, resulting in the formation of economically significant ore bodies.

A key role in gold concentration is played by reducing geochemical barriers associated with carbonaceous matter and zones of tectonic disturbances, where changes in redox conditions lead to the precipitation of gold from mobile forms.

The evolution of gold occurrence forms—from fine-grained and “hidden” forms to native gold—reflects changes in the physico-chemical parameters of the ore-forming system and can serve as an important indicator of the productivity of gold-bearing zones.

Based on a comprehensive analysis of geological, mineralogical, and geochemical data, a system of predictive geological criteria was formulated, and a predictive model for gold–carbonaceous–sulfide mineralization at the Bakyrshik deposit was proposed.

The proposed model and the identified predictive criteria can be applied in the forecasting, exploration, and assessment of gold potential in carbonaceous–terrigenous complexes within the gold-bearing belts of Kazakhstan and adjacent territories.

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**[www:nauka-nanrk.kz](http://www.nauka-nanrk.kz)
<http://www.geolog-technical.kz/index.php/en/>
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)**

Managing Editor: *T. Apendiev*
Editors: *D.S. Alenov, A.Shormakova*
Computer layout: *G.D. Zhadyranova*

Signed for print: July 10, 2026
Format: 70×90 1/16. 26.5 printed sheets. Order No. 3.