

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**

№5

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

5 (479)

September – Oktober 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.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 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 5.

Number 479 (2026), 414–431

<https://doi.org/10.32014/2026.2518-170X.711>

UDC: 553.411(574)

IRSTI: 38.49.17

©Zholtayev G.Zh., Umarbekova Z.T., Mashrapova M.A.* , Amanbaev R.A.,
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MODEL OF GOLD MINERALIZATION FORMATION AT THE BESTOBE DEPOSIT (NORTHERN KAZAKHSTAN)

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Abstract. Relevance. The Bestobe deposit, located within the Seletin ore district of Northern Kazakhstan, is one of the major quartz-vein gold deposits and represents a significant object for studying the regularities of gold–sulfide–quartz mineralization formation. Under conditions requiring the expansion of Kazakhstan’s mineral resource base and improvement of exploration efficiency, particular importance is attached to studies aimed at refining genetic models of ore formation, identifying factors controlling gold mineralization localization, and improving criteria for assessing concealed and deep-seated mineralization. Despite the long history of geological investigation and mining at the Bestobe deposit, questions concerning the stage-wise evolution of ore formation, the role of deep-seated faults, carbonaceous sequences, and hydrothermal fluids in the formation of economic gold concentrations remain debatable. **Objective.** The aim of the study is

to develop and substantiate a model for the formation of gold mineralization at the Bestobe deposit based on the analysis of its geological structure, structural–tectonic position, mineralization types, and stages of ore formation. *Methods.* The study is based on the integrated analysis of geological, structural–tectonic, mineralogical, and geochemical data on the Bestobe deposit. Field observation materials, results of ore composition studies, data on the morphology of quartz-vein bodies, textural and structural features of mineralization, as well as published and archival materials were used. Particular attention was paid to the role of fault structures, carbonaceous terrigenous-sedimentary sequences, and hydrothermal–metasomatic processes in the localization and redistribution of gold. *Results.* It was established that the distribution of gold mineralization is controlled by a system of deep-seated and fault-related structures of northeastern, latitudinal, and northwestern trends, which ensured prolonged and multiphase circulation of ore-forming fluids. Preparatory lithochemical, main quartz-vein, and late productive stages of ore formation were distinguished. It was shown that, during the early stage, dispersed gold and early sulfide mineralization accumulated within carbonaceous terrigenous-sedimentary sequences. The main stage is characterized by the formation of quartz veins, the development of banded, crustiform, and brecciated textures, and the generation of economic gold concentrations. During the late stage, processes of gold remobilization and redeposition were identified, resulting in the formation of high-fineness native gold and telluride- and bismuth-bearing mineral associations. *Conclusions.* The proposed model of gold mineralization formation at the Bestobe deposit refines current concepts of the mechanisms of gold–sulfide–quartz deposit formation and may be used to improve exploration criteria for assessing concealed and deep-seated mineralization in analogous geological and structural settings of Northern Kazakhstan.

Keywords: Bestobe deposit, quartz-vein mineralization, structural control, hydrothermal processes, ore-forming fluids, stages of ore formation

Funding: *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., Amanbaev R.A., Karatayeva G.M. Model of Gold Mineralization Formation at the Bestobe Deposit (Northern Kazakhstan). *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences.* 2026. No.5. Pp. 414–431. DOI: <https://doi.org/10.32014/2026.2518-170X.711>

©Жолтаев Г.Ж., Умарбекова З.Т., Машрапова М.А.*, Аманбаев Р.А.,
Қаратаева Г.М., 2026.

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БЕСТӨБЕ КЕНОРНЫНЫҢ (СОЛТҮСТІК ҚАЗАҚСТАН) АЛТЫН МИНЕРАЛДАНУЫНЫҢ ПАЙДА БОЛУ МОДЕЛІ

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Аннотация. *Өзектілігі.* Солтүстік Қазақстандағы Селеті кенді ауданы шегінде орналасқан Бестөбе кен орны кварц-желілі типтегі ірі алтын кен орындарының бірі болып табылады және алтын-сульфидті-кварцты минералданудың қалыптасу заңдылықтарын зерттеу үшін маңызды нысан саналады. Қазақстанның минералдық-шикізат базасын кеңейту және болжау-іздістіру жұмыстарының тиімділігін арттыру қажеттілігі жағдайында кен түзілуінің генетикалық модельдерін нақтылауға, алтын минералдануының локализациясын бақылайтын факторларды анықтауға және жасырын әрі терең орналасқан кенденуді бағалау критерийлерін жетілдіруге бағытталған зерттеулер ерекше өзектілікке ие. Бестөбе кен орны ұзақ уақыт бойы зерттеліп, игеріліп келе жатқанына қарамастан, кен түзілу процесінің сатылылығы, терең жарылымдардың, көміртекті қабаттардың және гидротермалдық флюидтердің өнеркәсіптік алтын шоғырларын қалыптастырудағы рөлі туралы мәселелер әлі де пікірталасты болып отыр. *Мақсаты.* Зерттеудің мақсаты – Бестөбе кен орнының геологиялық құрылысы, құрылымдық-тектоникалық жағдайы, минералдану типтері мен кен түзілу сатыларын талдау негізінде алтын минералдануының қалыптасу моделін әзірлеу және негіздеу. *Әдістері.* Зерттеу Бестөбе кен орны бойынша геологиялық, құрылымдық-тектоникалық, минералогиялық және геохимиялық деректерді кешенді талдауға негізделген. Далалық бақылау материалдары, рудалардың заттық құрамын зерттеу нәтижелері, кварц-желілі денелердің морфологиясы, минералданудың текстуралық-құрылымдық ерекшеліктері

жөніндегі мәліметтер, сондай-ақ жарияланған және қор материалдары пайдаланылды. Алтынның локализациясы мен қайта таралуындағы жарылымдық құрылымдардың, көміртекті терригенді-шөгінді қабаттардың және гидротермалдық-метасоматикалық процестердің рөліне ерекше назар аударылды. *Нәтижелері.* Алтын минералдануының орналасуы солтүстік-шығыс, ендік және солтүстік-батыс бағыттағы терең және жарылым маңы құрылымдарының жүйесімен бақыланатыны анықталды, бұл құрылымдар кен түзуші флюидтердің ұзақ мерзімді әрі көпфазалы айналымын қамтамасыз еткен. Кен түзілуінің дайындық литохимиялық, негізгі кварц-желілі және кеш өнімді сатылары ажыратылды. Ерте кезеңде көміртекті терригенді-шөгінді қабаттарда шашыраңқы алтын мен ерте сульфидті минералданудың жинақталуы жүргені көрсетілді. Негізгі кезең кварц желілерінің қалыптасуымен, жолақты, крустификациялық және брекчиялық текстуралардың дамуымен, сондай-ақ өнеркәсіптік алтын шоғырларының түзілуімен сипатталады. Кеш кезеңде алтынның ремобилизациясы мен қайта тұну процестері анықталып, нәтижесінде жоғары сынамалы табиғи алтын және теллуридті-висмутты минералдық ассоциациялар қалыптасқан. *Қорытындылар.* Ұсынылған Бестөбе кен орнының алтын минералдануының қалыптасу моделі алтын-сульфидті-кварцты кен орындарының түзілу механизмдері туралы қазіргі түсініктерді нақтылайды және Солтүстік Қазақстандағы ұқсас геологиялық-құрылымдық жағдайларда жасырын және терең орналасқан кенденуді бағалау кезінде болжау-іздістіру критерийлерін жетілдіру үшін пайдаланылуы мүмкін.

Кілт сөздер: Бестөбе кен орны, кварц-тамыр минералдануы, құрылымдық бақылау, гидротермиялық процестер, кен түзуші сұйықтықтар, кен түзілу кезеңдері

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Аннотация. *Актуальность.* Месторождение Бестобе, расположенное в пределах Селетинского рудного района Северного Казахстана, относится к числу крупных золоторудных объектов кварцево-жильного типа и представляет значительный научный интерес с точки зрения изучения закономерностей формирования золото-сульфидно-кварцевого оруденения. В условиях необходимости расширения минерально-сырьевой базы Казахстана и повышения эффективности геологоразведочных работ особую значимость приобретают исследования, направленные на уточнение генетических моделей рудообразования, выявление факторов локализации золотоносной минерализации и совершенствование прогнозно-поисковых критериев скрытого и глубинного оруденения. Несмотря на длительную историю геологического изучения и промышленной эксплуатации месторождения Бестобе, вопросы стадийности рудообразующих процессов, роли глубинных разломов, углеродистых толщ и гидротермальных флюидов в формировании промышленных концентраций золота остаются дискуссионными. *Цель.* Разработать и обосновать геолого-генетическую модель формирования золотого оруденения месторождения Бестобе на основе комплексного анализа его геологического строения, структурно-тектонического положения, особенностей минерализации и последовательности стадий рудообразования. *Методы.* Исследование основано на комплексном анализе геологических, структурно-тектонических, минералогических и геохимических данных по месторождению Бестобе. Используются материалы полевых геологических наблюдений, результаты изучения вещественного состава руд, данные о морфологии кварцево-жильных тел и текстурно-структурных особенностях минерализации, а также опубликованные научные и фондовые материалы. Особое внимание уделено анализу роли разломных структур, углеродистых терригенно-осадочных толщ и гидротермально-метасоматических процессов в локализации, миграции и перераспределении золота. *Результаты.* Установлено, что пространственное размещение золотой минерализации контролируется системой глубинных разломов и сопряженных с ними структур северо-восточного, широтного и северо-западного простирания, которые создавали условия для длительной многофазной циркуляции рудообразующих флюидов. В развитии золоторудной минерализации выделены три основных этапа: подготовительный литохимический, основной кварцево-жильный и поздний продуктивный. На подготовительном этапе происходили накопление рассеянного золота и формирование ранней сульфидной минерализации в углеродистых терригенно-осадочных толщах. Основным кварцево-жильный этап характеризовался формированием кварцевых жил, развитием полосчатых, крустификационных и брекчиевых

текстур, а также образованием промышленных концентраций золота. На позднем продуктивном этапе происходили ремобилизация и повторное осаждение золота с формированием высокопробного самородного золота, а также теллуридных и висмутсодержащих минеральных ассоциаций. Выявленная последовательность рудообразующих процессов отражает многоэтапный характер формирования золото-сульфидно-кварцевой минерализации месторождения Бестобе. *Выводы.* Предложенная геолого-генетическая модель формирования золотого оруденения месторождения Бестобе систематизирует представления о структурных, литологических и гидротермально-метасоматических факторах локализации золота. Установленная стадийность рудообразования и выявленная роль разломных структур могут служить основой для совершенствования прогнозно-поисковых критериев при выявлении скрытого и глубинного золотого оруденения. Полученные результаты представляют практический интерес для геологоразведочных работ в пределах сходных геолого-структурных обстановок Северного Казахстана.

Ключевые слова: месторождение Бестобе, кварцево-жильное оруденение, структурный контроль, гидротермальные процессы, рудообразующие флюиды, стадийность рудообразования.

Introduction. The development and refinement of genetic models of gold mineralization is one of the priority tasks of ore geology, as such models make it possible to synthesize the results of geological–structural, mineralogical, and geochemical studies and to apply them in the forecasting and exploration of new ore objects (Bekenov et al., 2016; Lebedev, 2019; Shestakov, 2018). The construction of models is especially relevant for large and long-exploited deposits, where a substantial body of factual material has been accumulated, yet the interpretation of ore-forming mechanisms remains debatable (Togizov et al., 2023).

The Bestobe deposit is one of the major gold deposits of Northern Kazakhstan and is characterized by a complex geological structure, a multistage ore-forming process, and a wide variety of ore morphology types. Gold mineralization is controlled by a system of deep-seated and fault-related structures and is associated with intense hydrothermal–metasomatic processes developed within Ordovician terrigenous and volcanogenic-sedimentary rocks, as well as in intrusive formations.

Despite the long history of geological investigation and industrial exploitation of the Bestobe deposit, issues related to the sources of ore-forming fluids, the conditions of gold migration and precipitation, the role of carbonaceous host sequences, and the stage-wise development and spatial zonation of the ore-forming process remain subjects of discussion. Existing concepts are often based on a fragmentary consideration of individual features—mineralogical, structural, or geochemical—without their comprehensive integration within a unified genetic model (Ivanov et al., 2020, Petrov and Zhuravlev, 2017).

In this context, the objective of the present study is to develop and substantiate

a model for the formation of gold mineralization at the Bestobe deposit based on an analysis of its geological structure, structural–tectonic position, types of mineralization, mineralogical associations, and stages of ore formation. The proposed model reflects the sequence and conditions of formation of various industrial ore types and can be used to refine exploration and prospecting criteria both within the deposit itself and in analogous geological–structural settings of Northern Kazakhstan.

Geological setting of the Bestobe deposit. The Bestobe deposit is located within the Seletin ore district of Northern Kazakhstan and is confined to the axial part of a narrow northeast-trending graben–syncline that forms part of the Seletin depression (Figure 1). In a regional geodynamic context, the deposit belongs to the Bestobe Ordovician island-arc metallogenic zone, which developed on Cambrian–Lower Ordovician oceanic crust (Bekenov et al., 2016; Kazybayeva et al., 2014; Samoilov and Lotsmanov, 2015).

The subsequent tectono-magmatic evolution of Kazakhstan was accompanied by the development of collisional and orogenic granitoid complexes reflecting the major stages of the geodynamic evolution of the region (Skrinnik et al., 2020).

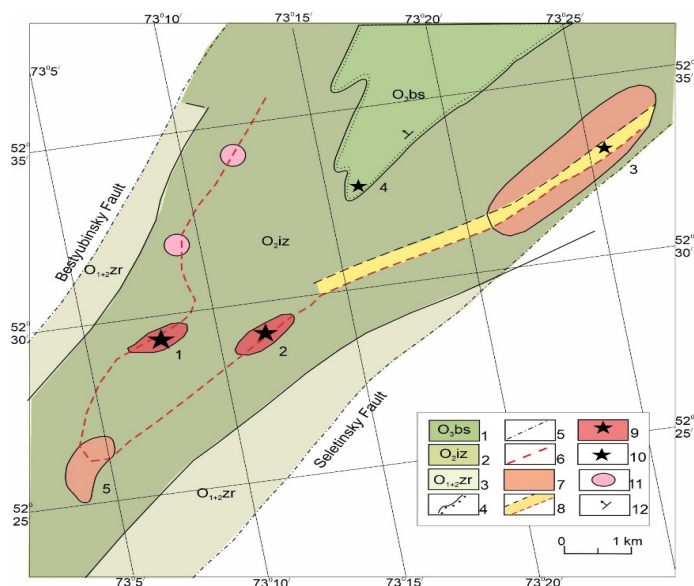


Figure 1. Schematic map of the distribution of deposits and ore occurrences of the Bestyubin ore field (after T. M. Zhautikov).

The ore-hosting sequence is predominantly composed of a terrigenous complex of Middle Ordovician deposits (Llanvirn–Lower Caradoc), assigned to the Izobilnaya Formation. Six lithological packages are distinguished within the section, differing in composition and depositional environments: from thick-bedded sandstones and siltstones with interlayers of volcanogenic material to thin-bedded

siliceous–argillaceous and carbonaceous siltstones. The rocks are characterized by a rhythmic flysch-like structure and a widespread presence of organic matter and syngenetic pyrite, which is of key importance for subsequent ore-forming processes (Lebedev, 2019; Spanov et al., 2019; Samoilov and Lotsmanov, 2015).

The general strike of the ore-hosting rocks is northeast, with predominantly northwestward steep dips (60–80°), locally vertical or overturned. Intrusive rocks within the deposit are represented by bodies of the Stepnyak intrusive complex and include quartz diorites, gabbro-diorites, plagiogranites, as well as numerous dikes of granite porphyries, plagiogranite porphyries, and diorite porphyrites. The intrusions are limited in size, steeply dipping, and spatially associated with fault zones.

The structural position of the deposit is defined by its location at the intersection of a graben–syncline with a deep-seated latitudinal fault. Within the ore field, near-fault folding and systems of faults of northeast, east–west, and northwest orientations are widely developed, forming a block-type structural pattern. The primary role in the localization of gold mineralization is played by shear faults of northeast strike, represented by zones of intensely schistosed and deformed rocks (Zhautikov, 2004; Zhautikov, 1987; Levin, 1984).

The combination of a carbon-rich Ordovician terrigenous sequence, intrusive bodies, and a well-developed fault system created favorable conditions for multistage hydrothermal ore formation. The persistence of ore parameters to considerable depths and the significant vertical extent of mineralization (exceeding 1.5 km) allow the Bestobe deposit to be regarded as a typical example of a deep-controlled quartz-vein gold deposit.

Materials and Methods. The study is based on the integrated analysis of geological, structural–tectonic, mineralogical, and geochemical data on the Bestobe gold deposit located within the Seletin ore district of Northern Kazakhstan. The research included the interpretation of published scientific literature, archival geological reports, фондовые материалы, and results of previous exploration and mining investigations conducted within the ore field.

Field geological observations were used to characterize the lithological composition of ore-hosting sequences, structural relationships, morphology of quartz-vein bodies, and spatial distribution of ore zones. Particular attention was paid to the analysis of fault systems of northeastern, latitudinal, and northwestern trends controlling the localization of gold mineralization.

Mineralogical and petrographic investigations included the study of ore textures, structural features of mineralization, mineral associations, and typomorphic characteristics of native gold and sulfides. The mineralogical composition of ores and hydrothermal alteration assemblages was analyzed using previously published analytical and microscopic data.

Geochemical interpretation was focused on the role of carbonaceous terrigenous–sedimentary sequences, hydrothermal–metasomatic processes, and geochemical barriers in the accumulation and redistribution of gold. Comparative

analysis of geological and genetic models of analogous quartz-vein and gold–sulfide–quartz deposits of Kazakhstan and Central Asia was also carried out.

The obtained data were integrated to develop a generalized model of gold mineralization formation at the Bestobe deposit and to identify the principal geological and structural criteria controlling ore localization and stage-wise evolution of the ore-forming system.

Results. *Structural and tectonic conditions of ore localization.* The structural and tectonic framework is the key factor controlling the localization of gold mineralization at the Bestobe deposit. The deposit is situated at the intersection of a northeast-striking graben–syncline with a deep-seated latitudinal fault, resulting in a complex network of faults and near-fault structures that govern the distribution of ore bodies.

Within the ore field, faults of northeast, latitudinal, and northwest orientations are widely developed. The most extensive and persistent are the northeast-striking faults, spaced 35–50 m apart, forming the backbone structure of the deposit. These faults are characterized by zones of intensely schistosed, cataclastic, and locally mylonitized rocks up to 0.7 m thick and serve as the primary ore-hosting structures.

Latitudinal and northwest-striking faults are less consistently developed but play an important role in forming a block-type structure of the ore field and creating zones of increased fracturing at intersections with northeast-striking faults (Figure 2). These structural intersections are characterized by the highest concentrations of quartz-vein and veinlet-disseminated gold mineralization.

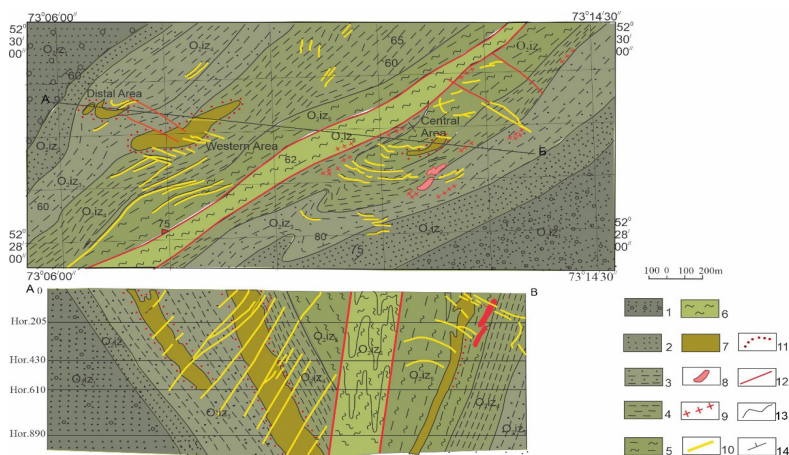


Figure 2. Schematic Geological Map and Cross-Section of the Bestube Deposit (after T.M. Zhautikov).

1 – coarse-layered rocks (iz_1); 2 – thin-layered sandstones, siltstones, and jaspers (iz_2); 3 – polymictic sandstones (iz_3); 4 – siliceous-clayey siltstones and argillites (iz_4); 5 – frequently interbedded sandstones and siltstones (iz_5); 6 – carbonaceous siltstones (iz_6); 7 – diorites, gabbro-diorites; 8 – plagiogranites; 9 – dikes; 10 – gold-bearing quartz veins; 11 – hornfels; 12 – faults; 13 – lithological boundaries; 14 – bedding elements.

Pre-ore and syn-ore deformations play a key role in the localization of ore bodies, determining the morphological diversity of quartz veins. In some cases, a stepped arrangement of veins and their fragmentation is observed, caused by displacements along pre-ore faults. Intra-ore and post-ore displacements are limited in extent and generally have small amplitudes, not disturbing the integrity of ore shoots (Levin, 1984; Askarova, 2022).

The structural control of mineralization is also reflected in the dependence of the morphology and length of quartz veins on the composition and physico-mechanical properties of the host rocks. In intrusive bodies and hornfelsed rocks, veins have clear contacts and considerable length, whereas in terrigenous and slate formations they occur as systems of short veinlets, lenses, and branching veins localized in zones of slaty cleavage.

Thus, the distribution of gold mineralization at the Bestobe deposit is determined by the combination of regional deep faults, near-fault folding, and local extensional and shear structures, creating favorable conditions for the circulation of ore-forming fluids and the formation of multi-stage quartz-vein and veinlet-disseminated mineralization (Bekenov et al., 2016; Rudenko and Fedorov, 2021).

Model of gold mineralization formation at the Bestobe deposit. The formation of gold mineralization at the Bestobe deposit is interpreted as the result of a multi-stage ore-forming process, controlled by the development of deep-seated faults, near-fault folding, and associated fluid activity. Based on structural, mineralogical, geochemical, and textural characteristics of the ores, three main stages of mineralization are distinguished, sequentially reflecting the evolution of the ore-forming system—from the formation of a lithochemically prepared environment to the development of crosscutting quartz-vein bodies. This interpretation aligns with contemporary understanding of the Bestobe deposit's genesis (Askarova, 2022).

During the early stage, the development of deep faults and near-fault deformations within the Ordovician terrigenous-carbonaceous sequence facilitated high rock permeability and created pathways for the circulation of early ore-bearing fluids. These fluids interacted with carbonaceous siltstones and tuffogenic-sedimentary rocks, initiating initial sulfide mineralization and setting the geochemical framework for subsequent gold deposition (Figure 3).

Stage I — Preparatory (lithochemical, pre-vein) stage

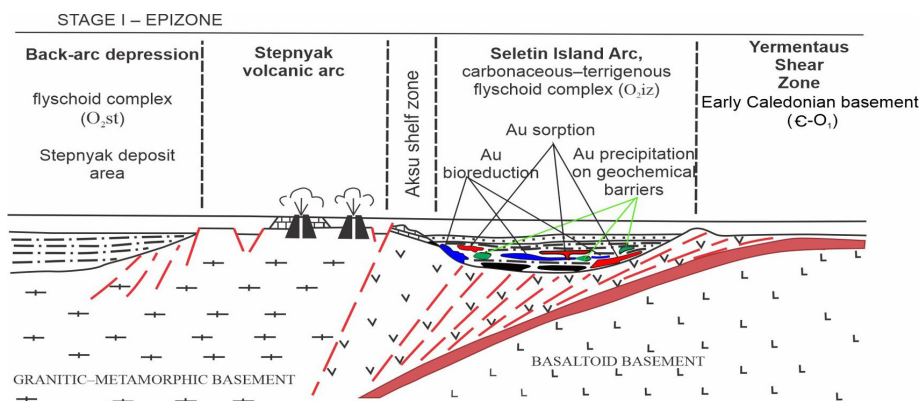


Figure 3. Geodynamic position and gold accumulation conditions at the early stage.

Fluids of this stage were characterized by high reactivity and promoted intensive hydrothermal–metasomatic transformations of the host rocks. The most widespread processes were chloritization, sericitization, carbonatization, and sulfidization, accompanied by the formation of disseminated early-generation pyrite and arsenopyrite. During this period, primary dispersed gold accumulated, mainly in a submicroscopic form associated with the early sulfides.

Thus, Stage I played a key role in forming a specific lithochemical environment enriched in metals and carbonaceous matter, which created a favorable geochemical background for subsequent concentrated ore formation (Lebedev, 2019; Sansyzbayeva et al., 2020; Rudenko and Fedorov, 2021; Fedorov and Kharitonov, 2019).

Stage II — Main ore stage (quartz vein stage)

The main stage of ore formation is associated with the activation of fault structures trending northeast, latitudinal, and northwest, which served as the primary channels for the upward migration of ore-forming fluids. During this period, quartz-vein mineralization develops, controlled by zones of shearing and extension (Figure 4).

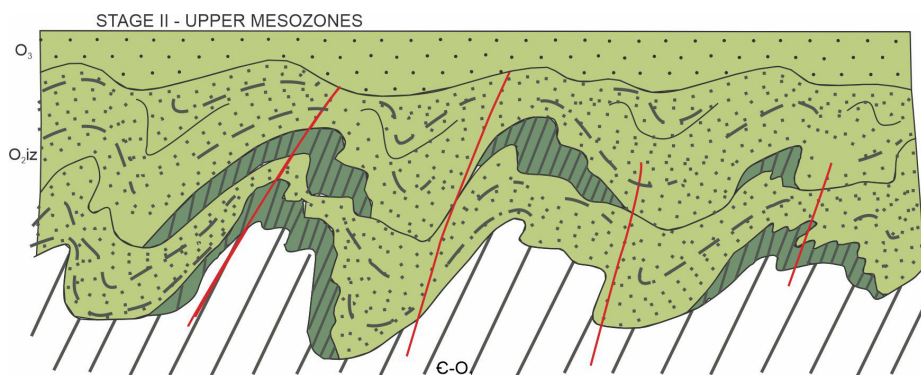


Figure 4. Structural conditions of quartz-vein mineralization formation (Stage II).

The fluids of Stage II were characterized by high mineralization and metal content, which led to the deposition of the main mass of quartz and sulfides, as well as the formation of industrial gold concentrations. Within the veins, massive-grained, banded, crustified, and brecciated textures developed, reflecting repeated crack openings and the pulsating nature of the fluid flow.

During this stage, gold was deposited predominantly in free form and was associated with pyrite, arsenopyrite, and polymetallic minerals. The formation of elongated ore pillars and bonanza ore zones is related to local areas of fault intersections and abrupt changes in the physicochemical parameters of the fluids (pressure, temperature, redox conditions) (Kuznetsov, 2018; Petrov and Zhuravlev, 2017; Fedorov and Kharitonov, 2019).

Stage III — Late productive (reworking and concentration of gold)

The late stage is characterized by a decrease in tectonic activity and a transition of the ore-forming system to a mode of local reworking of previously formed ore bodies. During this period, processes of partial leaching, migration, and redeposition of gold occur, accompanied by the formation of quartz–carbonate veins and late-stage veins.

The Stage III fluids had lower temperatures and a modified chemical composition, which facilitated the formation of high-grade native gold, tellurides, and bismuth-bearing minerals (Figure 5). It is at this stage that the richest ore shoots and large nuggets are formed, localized in areas of renewed fracturing and contacts between heterogeneous rock types.

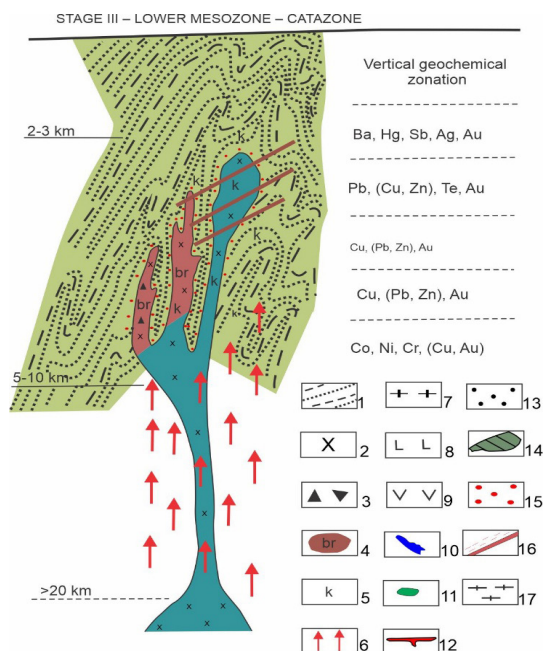


Figure 5. Deep model of the ore-forming system and vertical geochemical zonation.

The result of the III stage was the final redistribution of gold, accompanied by a sharp increase in its concentration in certain sections of veins and breccia bodies, which determined the high economic value of the deposit (Lebedev, 2019; Rudenko and Fedorov, 2021).

Comparison of the identified stages demonstrates the progressive evolution of the ore-forming system of the Bestobe deposit, from the development of a lithochemically prepared environment and the initial accumulation of dispersed gold to intensive quartz-vein ore formation, followed by the redistribution and local concentration of gold. Each stage is characterized by a specific combination of structural conditions, the nature of fluid activity, and the modes of gold occurrence, reflecting the directed evolution of a single hydrothermal system.

The prospecting indicators presented in Table 1 reflect the successive evolution of the ore-forming system of the Bestobe deposit and may be used to assess the potential for concealed and deep-seated gold mineralization. At the early stages of exploration, lithological and structural indicators are of primary importance, including the occurrence of carbonaceous terrigenous–sedimentary sequences, zones of schistosity, and early sulfide mineralization. At subsequent stages, intersections of fault structures, quartz-vein zones, and mineralogical and geochemical indicators of local gold concentration become increasingly important. The integrated combination of these indicators may be considered the most prospective criterion for identifying areas potentially hosting concealed and deep-seated gold mineralization (Table 1).

Table 1. Ore-forming stages and prospecting indicators of the Bestobe gold deposit.

Ore-forming stage	Ore-forming stage	Ore-forming stage	Ore-forming stage	Ore-forming stage	Ore-forming stage
I — Preparatory (lithochemical, pre-vein) stage	Development of deep-seated faults and near-fault deformation zones within the Ordovician carbonaceous terrigenous sequence; formation of enhanced permeability zones of enhanced permeability	Development of deep-seated faults and near-fault deformation zones within the Ordovician carbonaceous terrigenous sequence; formation of enhanced permeability zones of enhanced permeability	Development of deep-seated faults and near-fault deformation zones within the Ordovician carbonaceous terrigenous sequence; formation of enhanced permeability zones of enhanced permeability	Development of deep-seated faults and near-fault deformation zones within the Ordovician carbonaceous terrigenous sequence; formation of enhanced permeability zones of enhanced permeability	Carbonaceous siltstones and flysch-like sequences; zones of schistosity and enhanced fracturing; early pyrite–arsenopyrite mineralization; widespread hydrothermal–metasomatic alteration; geochemical anomalies of Au and associated elements.
II — Main ore-forming (quartz-vein) stage	Reactivation of northeast-, east-west-, and northwest-trending fault structures; development of shear and extensional zones	Reactivation of northeast-, east-west-, and northwest-trending fault structures; development of shear and extensional zones	Reactivation of northeast-, east-west-, and northwest-trending fault structures; development of shear and extensional zones	Reactivation of northeast-, east-west-, and northwest-trending fault structures; development of shear and extensional zones	Reactivation of northeast-, east-west-, and northwest-trending fault structures; development of shear and extensional zones
III — Late productive stage (gold remobilization and concentration)	Decrease in tectonic activity; local reactivation of fractures and contacts between lithologically contrasting rocks	Decrease in tectonic activity; local reactivation of fractures and contacts between lithologically contrasting rocks	Decrease in tectonic activity; local reactivation of fractures and contacts between lithologically contrasting rocks	Decrease in tectonic activity; local reactivation of fractures and contacts between lithologically contrasting rocks	Decrease in tectonic activity; local reactivation of fractures and contacts between lithologically contrasting rocks

Generalized scheme of the model. Overall, the model of gold mineralization formation at the Bestobe deposit reflects the sequential evolution of the system: structure → fluids → mineralization. Deep-seated faults and near-fault deformations provided pathways for fluid migration, carbonaceous terrigenous-sedimentary strata acted as geochemical barriers, and multi-stage hydrothermal activity led to the formation of large and stable industrial gold concentrations.

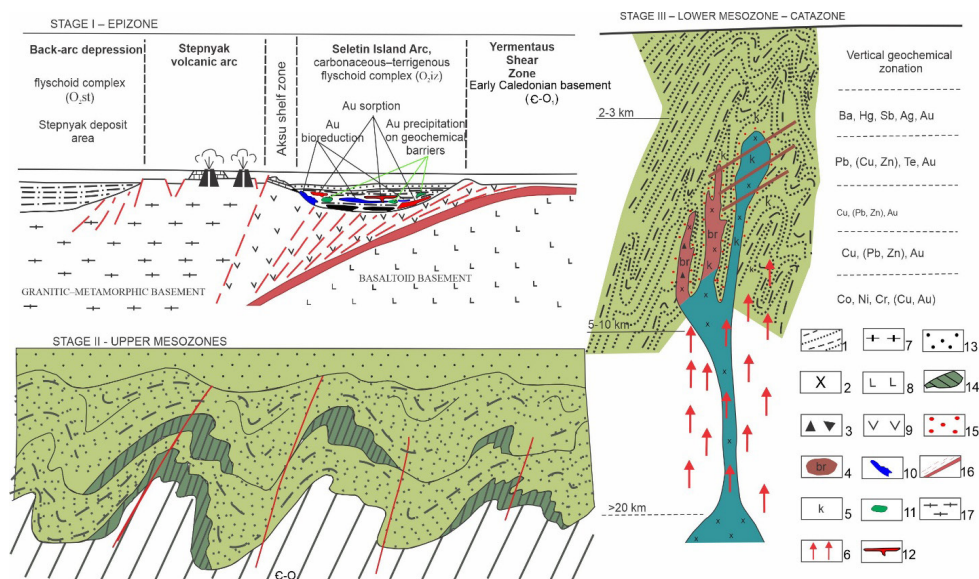


Figure 6. Generalized model of the formation of the Bestobe deposit.

1 – frequent interbedding of siltstones and sandstones; 2 – gabbro-diorites, quartz diorites, plagiogranites; 3 – magmatic breccias; 4 – beresitization; 5 – K-feldsparization; 6 – fluids; 7 – granito-metamorphic basement; 8 – basaltic basement; 9 – dikes; 10 – Au bioreduction; 11 – Au deposition at a geochemical barrier; 12 – Au sorption; 13 – sandstones; 14 – veinlet- and disseminated gold-sulfide stratiform ores; 15 – hornfels; 16 – subduction zone; 17 – flysch-like deposits.

Discussion. The proposed model of gold mineralization formation at the Bestobe deposit is well aligned with modern concepts of the genesis of quartz-vein and gold-sulfide-quartz deposits, which are widespread in the folded regions of Kazakhstan (Bekenov et al., 2016; Lebedev, 2019; Shestakov, 2018). The characteristic combination of deep structural control, multi-stage hydrothermal processes, and the active involvement of carbonaceous host rocks allow Bestobe to be considered a typical, yet illustrative, example of this industrial-genetic type of deposit.

Comparison of the obtained results with data from other large gold deposits in the region shows that, for the Bestobe deposit, as well as for several analogous objects, deep-seated and near-fault structures of northeast and latitudinal strike

play a decisive role in the localization of ore bodies. A similar role of structural control and prolonged circulation of ore-forming fluids has been considered in the prospecting model of gold mineralization developed for the Bakyrshik deposit (Umarbekova et al., 2019).

An important feature of the model is the identification of a preparatory lithochemical stage, during which a specific geochemical environment formed within the carbonaceous terrigenous–sedimentary sequences. The role of carbonaceous matter and black shale sequences in the accumulation, migration, and subsequent redistribution of gold has previously been considered using the Bakyrshik deposit as an example (Umarbekova et al., 2017a).

The accumulation of dispersed gold and early sulfides at this stage created the prerequisites for subsequent concentrated ore formation. Similar mechanisms of preliminary “enrichment” of host rocks have been observed at other gold–sulfide–quartz deposits and are considered one of the key factors for the high productivity of ore systems (Rudenko and Fedorov, 2021; Fedorov and Kharitonov, 2019; Yakovlev, 2022).

The main quartz-vein stage of ore formation at Bestobe is characterized by an episodic crack-opening regime and multi-phase mineral deposition, expressed in the wide development of banded, crustiform, and brecciated quartz textures. The formation of ore columns and bonanza zones is associated with local variations in the physico-chemical parameters of fluids at fault intersections, which corresponds to general patterns for the localization of high-grade gold in quartz-vein systems.

The late stage of remobilization and gold concentration, accompanied by the formation of high-grade native gold, tellurides, and bismuth-bearing minerals, gives the Bestobe deposit characteristics of a gold–tellurium–bismuth quartz subformation. This aligns it with several reference deposits in Kazakhstan and emphasizes the complex, evolutionary nature of the ore-forming system, in which early and late processes are closely interconnected. The obtained results are consistent with previously proposed concepts regarding the combined influence of geological structure, ore-controlling structures, and the composition of host sequences on the formation of gold ore systems in Kazakhstan (Umarbekova et al., 2017b).

Conclusion. The Bestobe deposit is confined to a structural node where a northeast-striking graben–syncline intersects with deep-seated faults, which defines the dominant role of structural–tectonic factors in the localization of gold mineralization and the formation of ore bodies with considerable vertical extent.

Ore formation at the deposit is multi-stage and occurs within a single evolving hydrothermal system, comprising sequential preparatory lithochemical, main quartz-vein, and late productive stages.

The main quartz-vein stage is associated with the activation of fault structures and episodic circulation of ore-forming fluids, resulting in the formation of industrially significant gold concentrations, well-developed ore columns, and bonanza zones at fault intersections.

The late stage is characterized by remobilization and localized concentration of gold, leading to the formation of high-grade native gold, telluride, and bismuth-bearing mineral associations, reflecting fluid composition evolution and changing physico-chemical conditions of ore formation.

The proposed model of gold mineralization formation at the Bestobe deposit can serve as a basis for refining exploration criteria, identifying hidden and deep-seated mineralization, and assessing the prospects of analogous gold deposits in Northern Kazakhstan.

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

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

Signed for print: Oktober 14, 2026
Format: 70×90 1/16. 26.5 printed sheets. Order No. 5.

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