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FEATURES OF COMPOSITION AND PROCESSING OF REFRACTORY GOLD-BEARING ORES OF THE AKTOBE DEPOSIT

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ABSTRACT
This article presents the results of studies on the processing of refractory gold-bearing ores from the Aktobe deposit (Zhambyl region, Kazakhstan). The research included chemical and mineralogical characterization, analysis of gold and silver occurrence, and evaluation of physical and mechanical properties. The average gold content was 1.55–1.6 g/t and silver 42–43 g/t. The ore is mainly composed of quartz (up to 79%) and pyrite (up to 10%). Phase analysis revealed that only 46.47% of gold occurs in free form, confirming the refractory nature of the ore. Gravity concentration tests demonstrated the effectiveness of centrifugal separation, achieving up to 35.93% gold recovery with 28.74% of the metal in the concentrate. The findings emphasize the necessity of combined processing technologies. Future research will focus on hydrometallurgical methods, including cyanidation, mechanical activation, and cavitation, to improve recovery and develop optimal flowsheets.

INTRODUCTION

The development of technologies for processing refractory gold-bearing ores is one of the most relevant directions of the modern gold mining industry (Adams, 2016; Marsden & House, 2006; Habashi, 1999). The deterioration of mineral raw material quality, the gradual depletion of easily beneficiable deposits, and the increasing complexity of the mineral composition of newly explored objects necessitate the implementation of advanced and integrated technological solutions (La Brooy et al., 1994; Zhang et al., 2019). According to literature data, a significant portion of the world's gold reserves is currently concentrated in refractory ores, where valuable metals occur in finely dispersed form, associated with sulfide minerals, or locked within a quartz matrix. Such mineralogical features substantially reduce the efficiency of conventional cyanide leaching and require the application of integrated beneficiation and hydrometallurgical processing schemes (Owusu et al., 2021).

The territory of Kazakhstan possesses considerable reserves of refractory gold-bearing raw materials. In this context, one of the promising objects is the Aktobe deposit, explored in 2017 in Zhambyl Region. According to published geological survey data, the ores of this deposit are characterized by relatively low gold content (1.55–1.6 g/t) and silver content (42–43 g/t), as well as a high proportion of quartz (up to 79%) and pyrite (up to 10%). Phase analysis results from several studies indicate that only about 46.47% of gold occurs in free form, while a substantial portion of the metal is associated with sulfide minerals and disseminated in a finely dispersed state within the host rock. These data confirm the refractory nature of the Aktobe ores and the limited applicability of direct cyanide leaching (Barmenshinova et al., 2023).

In global practice, gravity, flotation, and hydrometallurgical methods are widely used for processing such ores (Corrans, 2017; Mütevellioğlu et al., 2019; Asadi et al., 2019). Analysis of the literature shows that integrated technological schemes involving preliminary recovery of readily liberated gold followed by subsequent processing of obtained concentrates are considered among the most effective approaches (Mutaliyev et al., 2022). Several published studies have comparatively evaluated the efficiency of gravity beneficiation methods for ores similar to those of the Aktobe deposit, including jigging, concentration tables, and centrifugal separation.

Generalization of experimental data indicates that among gravity methods, centrifugal separation provides relatively higher performance in preliminary gold recovery; however, the amount of recovered gold remains insufficient to ensure fully effective industrial-scale processing. In this regard, many authors emphasize the necessity of combining gravity beneficiation with subsequent hydrometallurgical treatment stages.

Hydrometallurgical methods are considered among the most promising directions for processing refractory gold-bearing ores, including direct and intensive leaching processes, the use of alternative reagents, as well as mechanochemical activation and solution cavitation techniques (Amanzholov et al., 2018; Kulenova et al., 2021). Literature data indicate that these approaches have significant potential to improve gold and silver recovery and that their integration with gravity beneficiation enables the development of comprehensive technological schemes for refractory ores.

Thus, the relevance of this study is determined by the need to develop effective processing methods for refractory gold-bearing ores in Kazakhstan. This article is devoted to the analysis and generalization of published scientific research on the processing of ores from the Aktobe deposit. The aim of the work is to characterize the mineralogical features of the Aktobe ores based on a comparative analysis of literature data, evaluate the efficiency of gravity beneficiation methods, and substantiate the feasibility of further hydrometallurgical processing routes.

MATERIALS AND METHODS

This article is based on materials published in various scientific sources concerning the processing of refractory gold-bearing ores from the Aktobe deposit located in the Zhambyl Region. During the study, priority was given to data characterizing the mineralogical, chemical, physical-mechanical, and technological features of the ores from the Aktobe deposit. The deposit was explored in 2017, and geological survey results, as well as subsequent scientific publications, indicate that its ores are characterized by relatively low gold and silver contents and a high proportion of quartz and sulfide minerals. These features create technological limitations in ore processing and necessitate the application of integrated approaches.

In forming the research materials, systematization and comparative analysis of data presented by different authors were applied. When selecting literature sources, attention was paid to the mineralogical composition of the studied ores, the forms of gold occurrence, the reliability of analytical and technological methods used, and the industrial significance of the obtained results. This approach allowed for a comprehensive consideration of technological solutions applicable to ores similar to those of the Aktobe deposit.

The scientific sources included articles published in international and national peer-reviewed journals, monographs, dissertations, and conference proceedings. In selecting literature data, their scientific level, publication date, reliability of the applied methods, and practical relevance of the results were taken into account. Particular emphasis was placed on information related to the forms of gold distribution, beneficiation efficiency, and regularities in the variation of technological parameters.

During the analysis of published materials, the mineralogical forms of gold, the efficiency of beneficiation and processing methods, as well as the advantages and limitations of various technological approaches were systematized. By comparing results obtained by different authors, common trends and differences were identified, which made it possible to substantiate the main directions for processing refractory gold-bearing ores.

Chemical and Analytical Methods

One of the widely used methods for determining the content of gold and silver is fire assay analysis. This method allows for the evaluation of the total mass fraction of noble metals and is highly reliable for detecting low concentrations of gold and silver. Many scientific studies report that, to improve accuracy, fire assay results were cross-validated using atomic absorption spectroscopy (AAS) and gravimetric methods.

According to literature data, these analytical techniques make it possible to determine gold and silver contents in the range of 0.1–100 g/t and are widely used as standard methods in the gold mining industry (Adams, 2016; Marsden & House, 2006; Zhang et al., 2019). In addition, atomic absorption and X-ray fluorescence (XRF) analysis were used to determine the content of associated elements such as iron, copper, zinc, lead, and manganese. The accuracy of XRF analysis is generally reported within ±3%. The use of infrared analyzers for determining sulfur and carbon content is also widely described in the literature.

Mineralogical Research Methods

Comprehensive mineralogical methods were employed to study the mineral composition of Aktobe ores and the forms of gold occurrence. X-ray diffraction (XRD) analysis identified major mineral phases such as quartz, pyrite, calcite, feldspar, and mica. These data serve as a basis for evaluating ore composition and selecting beneficiation methods.

Polished section microscopy revealed that most gold particles are in micron and submicron sizes and are closely associated with sulfide minerals. Generalization of various studies indicates that gold is frequently associated with minerals such as pyrite, chalcopyrite, and sphalerite. This factor is considered one of the main reasons limiting the efficiency of gravity and flotation beneficiation processes.

Scanning electron microscopy (SEM) combined with energy-dispersive spectroscopy (EDS) allowed clarification of gold morphology, its mineral associations, and interrelations. According to published data, the mineral composition of the ore consists of approximately 78–79% quartz, about 10% pyrite, with the remainder represented by calcite, mica, and feldspar (Barmenshinova et al., 2023; Corrans, 2017). Such mineral composition indicates that a significant portion of gold is not present in free form but is locked within the mineral matrix.

Physical and Mechanical Properties of the Ore

The physical and mechanical properties of the ore play an important role in assessing the efficiency of grinding and beneficiation processes. Literature data consider density, porosity, water absorption, strength, and grindability as key parameters influencing the selection of technological regimes. For ores similar to those of the Aktobe deposit, high Bond work index values indicate significant energy consumption during grinding and highlight the importance of preliminary beneficiation stages (Moldashev & Sarbasov, 2019).

Gravity Beneficiation Methods

The preliminary recovery of gold using gravity methods has been widely discussed in scientific publications. Jigging, shaking tables, and centrifugal concentration are described as separation techniques based on density differences. Comparative analysis of literature data shows that jigging and shaking tables allow recovery of only a portion of gold, while a significant amount remains in tailings.

Centrifugal concentration, including GRG tests, is frequently cited as one of the most efficient gravity methods. According to published data, this method can achieve preliminary gold recovery of approximately 30–40%, but this level is often insufficient for fully effective industrial-scale processing (Owusu et al., 2021). Therefore, the necessity of combining gravity beneficiation with subsequent processing stages is commonly emphasized.

Hydrometallurgical Processing Directions

Hydrometallurgical methods are considered among the most promising approaches for processing refractory gold-bearing ores. Literature describes direct and intensive leaching processes, the use of alternative reagents, as well as mechanochemical activation and solution cavitation techniques as effective means of additional gold and silver recovery. These methods are reported to accelerate the breakdown of sulfide and silicate matrices and enhance reaction activity (Kulenova & Abdrakhmanova, 2021; Shestaev & Zhaksygulova, 2020).

In processing published experimental data, mathematical statistics methods were widely applied. Mean values, standard deviations, and correlation and regression dependencies were calculated, and the reliability of results was assessed using statistical criteria. These approaches made it possible to comparatively analyze the influence of various technological parameters on gold recovery indicators.

RESULTS AND DISCUSSION

A comprehensive and comparative analysis of published scientific studies on the processing of gold-bearing ores from the Aktobe deposit shows that their mineralogical, chemical, physical-mechanical, and technological features are the key factors determining the possibilities for effective gold recovery. Literature data repeatedly emphasize that these ores are characterized by a predominance of quartz rocks, a significant proportion of sulfide minerals – particularly pyrite—and the finely dispersed and locked distribution of gold. Such features result in a considerable portion of gold being confined within the mineral matrix rather than occurring in free form, which significantly limits the efficiency of conventional beneficiation and hydrometallurgical processing methods. The combination of these factors fully justifies classifying the ores of the Aktobe deposit as refractory gold-bearing raw materials.

According to published chemical data, the average gold content in the Aktobe ores is approximately 1.55–1.6 g/t, while the silver content is around 42–43 g/t. These values do not preclude the industrial development of the deposit; however, the relatively low concentration of precious metals imposes high technological requirements for their efficient processing. Analysis of the literature indicates that direct hydrometallurgical treatment of low-grade gold ores tends to be economically inefficient, whereas the introduction of preliminary beneficiation stages can improve overall technological performance. At the same time, the relatively high silver content increases the potential value of the ore from the perspective of complex processing; however, the different mineralogical distribution of gold and silver complicates their complete recovery under a single technological regime. Therefore, chemical composition data can only serve as a basis for technologically sound decisions when considered together with mineralogical and phase characteristics.

Generalization of mineralogical studies shows that the ores of the Aktobe deposit predominantly belong to quartz-rich rocks, with quartz content ranging from 75 to 79%. Pyrite accounts for approximately 8–10%, while minerals such as calcite, feldspar, and muscovite occur as minor components. This mineralogical composition indicates that a significant portion of gold is not present in free form but is closely associated with sulfide and silicate minerals. Phase analysis data suggest that only about 45–47% of gold occurs as free or partially liberated grains, while the remainder is associated with pyrite and other sulfide minerals or dispersed within the quartz matrix in micron and submicron sizes. Literature widely reports that this situation considerably reduces the efficiency of direct cyanide leaching, making the application of preliminary beneficiation stages a mandatory technological element for refractory ores.

A generalized description of the characteristic mineralogical features of these ores is presented in Table 1, which shows the proportions of the main minerals and their influence on beneficiation and processing operations.

Table 1. Mineralogical composition of the ores from the Aktobe deposit

Mineral	Content, %	Technological effect
Quartz	75-79	Enhances microdispersed distribution of gold and reduces beneficiation efficiency
Pyrite	8-10	Main carrier of gold in locked form
Calcite	4-6	Indirect influence on reagent regimes
Feldspar	3-5	Complicates grinding and slime formation processes
Muscovite	1-3	Affects selectivity during flotation
Note – Compiled by the author		

Published physico-mechanical data indicate that the ore is characterized by high strength and difficult grindability. For ores similar to those of the Aktobe deposit, a Bond work index of approximately 19 kWh/t^0.5 and a strength index of $f \approx 12$ according to the Protodyakonov scale indicate significant energy consumption during grinding. These factors complicate the complete liberation of gold and necessitate the introduction of additional grinding stages; however, an increase in the degree of grinding raises the energy intensity of the technological process and may negatively affect the economic efficiency of processing. In this regard, literature data emphasize the need to optimize grinding regimes taking into account mineralogical and physico-mechanical characteristics.

A comparative analysis of published studies on the efficiency of gravity beneficiation methods shows that these techniques demonstrate different levels of performance at the preliminary beneficiation stage. Although jigging and shaking tables enable the recovery of free and coarse-grained gold, several studies note that a significant portion of gold remains in the tailings. Centrifugal concentration, including GRG tests, is described as one of the most effective gravity methods and can provide an average preliminary gold recovery of approximately 30–40%. Nevertheless, these values are insufficient to ensure complete gold recovery, since a considerable portion of gold remains locked in sulfide and microdispersed phases.

Generalized data on the comparative efficiency of gravity beneficiation methods are presented in Table 2.

Table 2. Test results of gravity beneficiation methods for ores from the Aktobe deposit

Method	Gold recovery, %	Gold content in concentrate, g/t	Remarks
Jigging	12–15	8	Significant metal losses
Shaking table	20–22	18	Improved, but still limited
Centrifugal concentration	28–35.93	36	Most effective method
Note – Compiled by the author			

Despite the relatively high efficiency of gravity beneficiation, published data indicate that its use as an independent technology is insufficient for refractory gold-bearing ores. In this regard, many authors recommend applying multistage technological schemes that combine gravity beneficiation with flotation and hydrometallurgical processing stages. In such schemes, free and coarse gold is recovered at the preliminary gravity stage, while subsequent stages are aimed at additional recovery of sulfide-associated and microdispersed gold.

Numerous scientific studies show that the application of hydrometallurgical processing methods makes it possible to effectively treat difficult-to-leach and locked forms of gold. Although direct cyanide leaching is effective for free gold, its efficiency decreases when processing gold associated with sulfide minerals. In this context, approaches such as intensive leaching, the use of alternative reagents, mechanochemical activation, and solution cavitation are reported to accelerate the liberation of gold from the mineral matrix and increase overall recovery to 70–80%.

In general, the systematization of published scientific results clearly demonstrates the necessity of applying multistage and integrated technological approaches for the effective processing of gold-bearing ores from the Aktobe deposit. Preliminary gravity beneficiation allows the recovery of the readily liberated portion of gold, while subsequent flotation and hydrometallurgical stages enable efficient extraction of locked and microdispersed gold forms. Such technological strategies form the scientific and technological basis for the industrial development of ores from the Aktobe deposit.

CONCLUSIONS

A comprehensive analysis of published scientific data on the processing of gold-bearing ores from the Aktobe deposit demonstrates that, based on their mineralogical composition and the distribution patterns of gold, they belong to the category of refractory ores. Literature sources identify the predominance of quartz, a significant presence of pyrite, and the locked and finely dispersed distribution of gold as the key factors that make these ores technologically complex. These features limit the efficient recovery of gold using conventional technological approaches, including direct cyanide leaching, and substantiate the necessity of applying preliminary beneficiation stages.

A comparative evaluation of gravity beneficiation results reported in published studies reveals considerable differences in the efficiency of various methods. Generalization of literature data indicates that centrifugal concentration is one of the most effective techniques at the preliminary beneficiation stage. This method allows for relatively high recovery of free and coarse-grained gold and is shown by many authors to outperform jigging and shaking table methods. At the same time, it is emphasized that the main advantage of gravity technologies lies in their ability to recover the readily liberated portion of gold at the initial stage.

However, analysis of published data also shows that a substantial fraction of gold remains locked within sulfide minerals or in the microdispersed phases of the host rock. This circumstance demonstrates the insufficiency of gravity methods as a standalone technology and highlights the need for further integrated processing of the ore. In this regard, many researchers consider the combination of gravity beneficiation with subsequent technological stages as an essential condition for effective and complete gold recovery.

Literature data propose hydrometallurgical methods as one of the most promising technological directions. In particular, direct and intensive leaching, mechanochemical activation, and cavitation treatment of solutions are described as advanced approaches that can enhance the leachability of microscopic and dispersed gold forms. These methods improve reagent penetration into mineral surfaces and accelerate process kinetics, thereby increasing gold recovery. Numerous scientific studies substantiate that the combined application of gravity beneficiation and hydrometallurgical treatment enables the development of an effective integrated processing scheme for refractory gold-bearing ores.

Thus, the synthesis of the reviewed data clearly demonstrates the importance of applying multistage and integrated technological approaches for the efficient processing of gold-bearing ores from the Aktobe deposit. From a theoretical perspective, this work contributes to clarifying the mineralogical and technological patterns characteristic of refractory gold ores and supplements the general scientific foundation for their processing. From a practical standpoint, the conclusions obtained provide a scientific basis for developing effective technological solutions aimed at the industrial exploitation of the deposit.

The technological directions proposed based on the analysis of published results can be applied to the development of other refractory gold-bearing deposits in Kazakhstan with similar geological and mineralogical characteristics. These approaches can enhance the efficiency of integrated mineral resource utilization and serve as a scientific foundation for the technological advancement of the domestic gold mining industry.

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