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*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).*

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[1]Navoi Mining and Metallurgical Company, Navoi, Uzbekistan;
[2]Navoi State University of Mining and Technologies, Navoi, Uzbekistan;
[3]Satbayev University, Almaty, Kazakhstan.
[*]E-mail: a.kuttybayev@satbayev.university

# STUDY OF FLOTATION CONCENTRATES OF AUMINZO-AMANTAY SULFIDE ORES AND IMPROVEMENT OF GOLD RECOVERY

**Sanakulov Kuvandik** — Doctor of Technical Sciences, Professor, Navoi Mining and Metallurgical Company, Navoi, Uzbekistan,
E-mail: info@ngmk.uz, https://orcid.org/0000-0002-9998-4366;
**Ergashev Ulugbek** — Doctor of Technical Sciences, Professor, Navoi Mining and Metallurgical Company, Navoi, Uzbekistan,
E-mail: info@ngmk.uz, https://orcid.org/0000-0002-2043-0046;
**Khamidov Rustam** — PhD Doctor of Philosophy in Technical Sciences, Navoi State University of Mining and Technologies, Navoi, Uzbekistan,
E-mail: hamidov-88@mail.ru, https://orcid.org/0000-0001-8998-6571;
**Kuttybayev Aidar** — Candidate of Technical Sciences, Professor, Satbayev University, Almaty, Kazakhstan,
E-mail: a.kuttybayev@satbayev.university, https://orcid.org/0000-0003-3997-8324;
**Kozhantov Arystan** — Candidate of Technical Sciences, Professor, Satbayev University, Almaty, Kazakhstan,
E-mail: a.kozhantov@satbayev.university, https://orcid.org/0000-0002-3658-9940.

**Abstract.** *Relevance.* Sulfide flotation concentrates from the Auminzo-Amantay deposit are characterized by a complex mineralogical composition, the presence of carbonaceous matter, the occurrence of gold as nano-scale inclusions. These features classify the material as refractory gold-bearing feedstock. At present, these concentrates are processed at Hydrometallurgical Plant No.5 of the Navoi Mining and Metallurgical Company using conventional cyanidation, where gold recovery does not exceed 50%. Therefore, the development of effective pre-treatment technologies to improve gold extraction is highly relevant. *Objective.* This study aims to investigate and comparatively evaluate modern processing technologies for refractory gold ores in order to enhance gold recovery from sulfide flotation concentrates of the Auminzo-Amantay deposit. *Methods.* The mineralogical and technological properties of the concentrates were examined, modern refractory gold processing methods were reviewed. A comparative assessment was conducted for oxygen-slurry treatment, bacterial oxidation (BIOX), oxidative roasting. For each method, the degree of sulfide mineral decomposition, the effect on carbonaceous matter, and subsequent gold recovery by cyanidation were evaluated. In addition, economic efficiency and environmental impacts were analyzed, including energy consumption, the feasibility of industrial-scale implementation under existing plant conditions. *Results and conclusions.* The BIOX process provides a high degree of sulfide oxidation; however, carbonaceous matter leads to preg-robbing effects, reducing gold recovery. Oxidative roasting ensures near-complete sulfide destruction and reduces carbon content, but a portion of gold remains locked in pyrrhotite in nano-scale forms. Oxygen-slurry treatment achieves ultra-fine grinding, yet the formation of secondary minerals such as jarosite limits overall efficiency. Even with these pre-treatment methods, gold recovery did not exceed 70-75%. The main limiting factors are the dual refractory nature of the concentrate, carbonaceous matter, and submicroscopic gold occurrence. To improve processing efficiency, integrated flowsheets combining oxidative roasting, carbon deactivation, and optimized cyanidation parameters are recommended. These approaches can significantly enhance gold recovery and overall ore processing performance.

**Keywords:** refractory ores, flotation concentrate, gold, nanogold, cyanidation, oxidative roasting

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[1]«Навои тау-металлургия комбинаты» АҚ, Навои, Өзбекстан;
[2]Навои мемлекеттік тау-металлургиялық университеті, Навои, Өзбекстан;
[3]Satbayev университеті, Алматы, Қазақстан.
[*]E-mail: a.kuttybayev@satbayev.university

## АУМИНЗО-АМАНТАЙ СУЛЬФИДТІ КЕНІ ФЛОТАЦИЯЛЫҚ КОНЦЕНТРАТТАРЫН ЗЕРТТЕУ ЖӘНЕ АЛТЫНДЫ АЛУ ТИІМДІЛІГІН АРТТЫРУ

**Санакулов Кувандик** — техникалық ғылымдарының докторы, профессор, АҚ «Навои тау-металлургия комбинаты», Навои, Өзбекстан,
E-mail: info@ngmk.uz, https://orcid.org/0000-0002-9998-4366;

**Эргашев Улугбек** — техникалық ғылымдарының докторы, профессор, АҚ «Навои тау-металлургия комбинаты», Навои, Өзбекстан,
E-mail: info@ngmk.uz, https://orcid.org/0000-0002-2043-0046;
**Хамидов Рустам —** PhD, Навои мемлекеттік тау-технология университеті, Навои, Өзбекстан,
E-mail: hamidov-88@mail.ru, https://orcid.org/0000-0001-8998-6571;
**Құттыбаев Айдар —** техника ғылымдарының кандидаты, профессор, Satbayev University, Алматы, Қазақстан,
E-mail: a.kuttybayev@satbayev.university, https://orcid.org/0000-0003-3997-8324;
**Қожантов Арыстан —** техника ғылымдарының кандидаты, профессор, Satbayev University, Алматы, Қазақстан,
E-mail: a.kozhantov@satbayev.university, https://orcid.org/0000-0002-3658-9940.

**Аннотация.** *Өзектілігі.* Ауминзо – Амантай кен орнының сульфидті флотациялық концентраттары күрделі минералогиялық құрамымен, көміртекті заттардың болуымен және алтынның наноөлшемді қосындылар түрінде таралуымен сипатталады. Бұл ерекшеліктер аталған шикізатты байытуы қиын алтынқұрамды материалдар санатына жатқызады. Қазіргі уақытта Навоий тау-кен металлургия комбинаты құрамындағы ГМЗ - 5 гидрометаллургиялық зауытында концентраттарды өңдеу дәстүрлі циандау әдісімен жүзеге асырылады, мұнда алтынды алу көрсеткіші 50 % - дан аспайды. Осыған байланысты алтынды алу дәрежесін арттыруға бағытталған тиімді алдын ала өңдеу технологияларын әзірлеу өзекті мәселе болып табылады. *Мақсаты.* Ауминзо - Амантай кен орнының сульфидті флотациялық концентраттарынан алтынды тиімді алу үшін қиын алынатын алтынды өңдеудің заманауи технологияларын зерттеу және олардың тиімділігін салыстырмалы бағалау. *Әдістері.* Зерттеу барысында концентраттардың минералогиялық және технологиялық ерекшеліктері қарастырылып, қиын алынатын алтынды өңдеудің заманауи әдістері талданды. Оттекті-шламдық өңдеу, бактериялық тотықтыру (BIOX) және тотықтырғыш күйдіру технологияларының тиімділігі салыстырмалы түрде бағаланды. Әр технология бойынша сульфидті минералдардың ыдырау дәрежесі, көміртекті заттарға әсері және кейінгі циандау кезіндегі алтынды алу көрсеткіштері анықталды. Сонымен қатар, процестердің энергия сыйымдылығы, экологиялық аспектілері, реагенттік шығындары және өндірістік жағдайда енгізу мүмкіндіктері бағаланды. *Нәтижелері мен қорытындылары.* BIOX технологиясы жоғары десульфуризация деңгейін қамтамасыз ететіні анықталды, алайда көміртекті заттардың болуы алтынның сорбциялық жұтылуына әкеліп, оны алу көрсеткіштерін төмендетеді. Тотықтырғыш күйдіру сульфидтердің толық дерлік ыдырауына ықпал етеді, бірақ алтынның бір бөлігі пирротинде наноөлшемді күйде сақталады. Оттекті - шламдық өңдеу кезінде аса ұсақ ұнтақтау жүзеге асады, дегенмен ярозит секілді екінші реттік минералдардың түзілуі процестің тиімділігін шектейді. Қарастырылған технологияларды қолданғанның өзінде алтынды алу деңгейі

70–75 %-дан аспады. Зерттеу нәтижелері концентраттардың қосарлы қиын байытылатын қасиеті, көміртекті заттардың болуы және алтынның жасырын таралу формалары негізгі шектеуші факторлар екенін көрсетті. Сондықтан алтынды алу тиімділігін арттыру үшін тотықтырғыш күйдіруді, көміртекті заттарды бейтараптандыруды және циандау параметрлерін оңтайландыруды қамтитын кешенді технологиялық сұлбаларды қолдану ұсынылады. Ұсынылған тәсілдер өндірістік тиімділікті арттырып, бағалы компоненттерді кешенді игеру көрсеткіштерін жақсартуға мүмкіндік береді.

**Түйін сөздер:** қиын игерілетін кендер, флотациялық концентрат, алтын, наноалтын, цианизация, оксидтік күйдіру

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[1]АО «Навойский горно-металлургический комбинат», Навои, Узбекистан;
[2]Навойский государственный горно-металлургический университет, Навои, Узбекистан;
[3]Satbayev University, Алматы, Қазақстан.
[*]E-mail: a.kuttybayev@satbayev.university

# ИССЛЕДОВАНИЕ ФЛОТАЦИОННЫХ КОНЦЕНТРАТОВ СУЛЬФИДНЫХ РУД АУМИНЗО-АМАНТАЙ И УЛУЧШЕНИЕ ИЗВЛЕЧЕНИЯ ЗОЛОТА

**Санакулов Кувандик** — доктор технических наук, профессор, АО «Навойский горно-металлургический комбинат», Навои, Узбекистан,
E-mail: info@ngmk.uz, https://orcid.org/0000-0002-9998-4366;
**Эргашев Улугбек** — доктор технических наук, профессор, АО «Навойский горно-металлургический комбинат», Навои, Узбекистан,
E-mail: info@ngmk.uz, https://orcid.org/0000-0002-2043-0046;
**Хамидов Рустам** — PhD, Навойский государственный горно-технологический университет, Навои, Узбекистан,
E-mail: hamidov-88@mail.ru, https://orcid.org/0000-0001-8998-6571;
**Куттыбаев Айдар** — кандидат технических наук, профессор, Satbayev University, Алматы, Казахстан,
E-mail: a.kuttybayev@satbayev.university, https://orcid.org/0000-0003-3997-8324;
**Кожантов Арыстан** — кандидат технических наук, профессор, Satbayev University, Алматы, Казахстан,
E-mail: a.kozhantov@satbayev.university, https://orcid.org/0000-0002-3658-9940.

**Аннотация.** *Актуальность.* Сульфидные флотационные концентраты месторождения Ауминзо-Амантáй характеризуются сложным минералогическим составом, наличием углеродистых веществ и распространением золота в виде наноразмерных включений, что обусловливает их принадлежность к категории труднообогатимого золотосодержащего сырья. В настоящее время на гидрометаллургическом заводе № 5 (ГМЗ-5) Навоийского горно-металлургического комбината переработка данных концентратов осуществляется методом традиционного цианирования, при котором извлечение золота не превышает 50%. В связи с этим актуальной задачей является разработка эффективных технологий предварительной подготовки сырья, направленных на повышение степени извлечения золота. *Цель*. Исследовать и провести сравнительную оценку эффективности современных технологий переработки трудноизвлекаемого золота для повышения степени извлечения золота из сульфидных флотационных концентратов месторождения Ауминзо-Амантáй. *Методы*. В ходе исследования изучены минералогические и технологические особенности концентратов, а также рассмотрены современные методы переработки трудноизвлекаемого золота. Проведена сравнительная оценка эффективности кислородно-шламовой обработки, бактериального окисления (BIOX) и окислительного обжига. Для каждой технологии определялись степень разрушения сульфидных минералов, влияние на углеродистое вещество и показатели последующего извлечения золота методом цианирования. Дополнительно выполнен анализ экономической эффективности и экологических аспектов рассматриваемых процессов, включая оценку энергоемкости и перспектив промышленного внедрения исследуемых технологий в условиях действующего производства. *Результаты и выводы.* Установлено, что технология BIOX обеспечивает высокую степень десульфуризации, однако наличие углеродистых веществ вызывает эффект сорбционного поглощения золота, что снижает показатели его извлечения. Окислительный обжиг способствует практически полному разрушению сульфидов и уменьшению содержания углерода, однако часть золота сохраняется в пирротине в наноразмерной форме. При кислородно-шламовой обработке достигается сверхтонкое измельчение концентрата, но образование вторичных минералов, таких как ярозит, ограничивает эффективность процесса. Даже при применении указанных технологий извлечение золота не превышает 70–75%. Основными факторами, ограничивающими извлечение золота, являются двойная упорность концентратов, наличие углеродистых веществ и скрытые формы нахождения золота. Для повышения эффективности переработки рекомендуется применение комбинированных технологических схем, включающих окислительный обжиг, нейтрализацию углеродистых веществ и оптимизацию параметров цианирования. Предложенные подходы позволяют повысить технологическую эффективность извлечения золота и улучшить показатели комплексной переработки рудного сырья.

**Ключевые слова:** труднообогатимые руды, флотационный концентрат, золото, нанозолото, цианирование, окислительный обжиг

**Introduction**. Mining plays a key role in supplying the country’s economy with valuable metals such as gold, silver, and others (Hryhoriev et al., 2023a; Hryhoriev et al., 2023b; Kuttybayev et al., 2025). One of the main objectives of the mining industry is not only the efficient extraction of ore (Lutsenko et al., 2023; Zeitinova et al., 2024) but also its high-quality processing to maximize the recovery of valuable components. In this context, increasing attention is given to complex and refractory ores, where conventional processing routes fail to ensure sufficient metal recovery. Of particular importance in this field are flotation concentrates of sulfide ores, especially from deposits such as Auminzo–Amantai, which are characterized by a complex and heterogeneous mineralogical composition, fine intergrowths of valuable and gangue minerals, and the presence of carbon-bearing phases. Despite significant geological reserves, gold extraction from such ores is associated with a range of technological and physicochemical challenges (Koroviaka et al., 2023), necessitating the application of advanced beneficiation and hydrometallurgical treatment methods.

Flotation concentrates of sulfide ores from the Auminzo–Amantoy deposit are classified as refractory raw materials, from which gold recovery is extremely difficult under conventional processing conditions (Sanakulov et al., 2023; Afenya, 1991; Marsden et al., 2006). In standard flotation–hydrometallurgical schemes, the efficiency of cyanidation does not exceed 50%, which is primarily attributed to the complex mineralogical structure, the presence of naturally occurring carbonaceous matter with high sorption activity, and the extremely fine dissemination of gold within sulfide matrices (La et al., 1994; Ubaldini et al., 1998; Biletskiy et al., 2020). These factors collectively result in both physical encapsulation and chemical loss mechanisms during leaching.

To enhance gold recovery, several pretreatment methods have been investigated, including oxygen-lime treatment, bacterial oxidation (BIOX), and oxidative roasting. These technologies aim to destroy sulfide matrices and reduce the negative impact of carbonaceous components. However, even after optimization of these processing schemes, the overall recovery of the valuable component remains insufficient for industrial efficiency requirements (Miller et al., 2005; Wang et al., 2016), highlighting the need for further improvement of integrated processing strategies.

**Materials and methods of research.** The phase and structural characterization of the studied samples was carried out using powder X-ray diffraction (XRD) analysis with subsequent structure refinement by the Rietveld method, enabling quantitative phase identification and precise determination of crystallographic parameters. Microstructural and morphological features of the ore and processed products were investigated using scanning electron microscopy (SEM), providing detailed information on mineral associations, particle morphology, and the distribution of fine-grained phases.

In addition, a comprehensive analysis of solid residues obtained after different pretreatment techniques was performed, including oxygen–lime treatment (OLT), BIOX bio-oxidation, and oxidative roasting followed by sorption cyanidation. These comparative experiments were aimed at evaluating the influence of different oxidation regimes on mineral transformation, sulfide breakdown, and gold liberation efficiency. The methodological approach was supported by previously established procedures reported in the literature (Hryhoriev et al., 2023a; Liu et al., 2004; Baltabekova, et al., 2025), ensuring consistency with standard practices in hydrometallurgical and mineral processing research.

**Results.** The compositional analysis of the flotation concentrate (Table 1) indicates that the material is predominantly composed of pyrite, quartz, and a substantial proportion of silicate minerals, accompanied by a notable content of amorphous carbonaceous matter (up to 10 wt.%). In addition to these major phases, minor amounts of accessory minerals are also present, reflecting the complex and heterogeneous nature of the ore matrix. The coexistence of sulfide and silicate phases creates a structurally intricate assemblage that complicates mineral liberation during both comminution and subsequent hydrometallurgical processing stages.

The presence of this carbonaceous component is particularly significant, as it is known to exhibit strong preg-robbing behavior by adsorbing gold–cyanide complexes from solution, thereby reducing overall gold recovery efficiency. Such behavior has been widely reported in refractory gold ores and is attributed to the high surface reactivity, micro-porosity, and adsorption capacity of amorphous carbon phases (Liu et al., 2000; Yang et al., 2002). In addition, the fine dissemination of carbonaceous matter within sulfide and silicate matrices further enhances its interaction with dissolved gold species, intensifying losses during cyanidation.

Moreover, the distribution of pyrite as the dominant sulfide mineral suggests that a significant portion of gold may be structurally or physically associated with pyrite lattices, either through lattice substitution or micro-inclusions. This association further contributes to the refractory nature of the material, as it limits direct exposure of gold to leaching reagents. The combined effect of sulfide encapsulation and carbonaceous preg-robbing behavior therefore results in a dual mechanism of gold loss, which significantly constrains metallurgical performance.

Overall, the mineralogical features identified in the flotation concentrate confirm its classification as a complex double-refractory gold-bearing material, requiring advanced pre-oxidation or deactivation strategies to mitigate carbon-related gold adsorption and to enhance subsequent cyanide leaching efficiency.

X-ray phase analysis confirmed the predominance of quartz and pyrite (Fig. 1).

Table 1. Mineralogical structure of the flotation concentrate.

| **Mineral** | **Content, %** |
|---|---|
| Pyrite | 24,1 |
| Quartz | 19,2 |
| Muscovite | 18,3 |
| Albit | 8,9 |
| Chlorite | 7 |
| Carbonaceous matter | 10,1 |
| Other (anorthite, calcite, etc.) | ~12,4 |

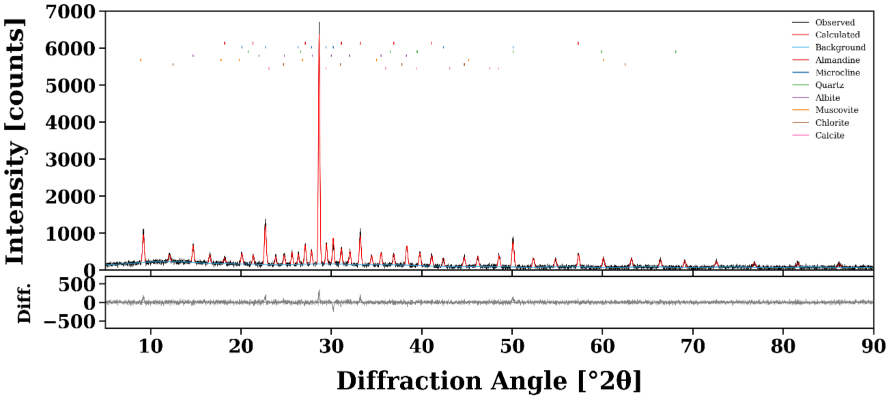


Figure 1. Powder diffractogram of flotation concentrate.

The results obtained from the investigation of the flotation concentrate clearly indicate the necessity of efficient liberation of refractory gold from the sulfide mineral matrix. The mineralogical complexity of the material, combined with the fine dissemination of gold within sulfide phases, requires advanced pretreatment strategies capable of breaking down or transforming the host minerals prior to cyanidation. In particular, the presence of gold locked at the micro- and nanoscale within pyrite and associated sulfides significantly restricts direct leaching efficiency, thereby necessitating multistage processing schemes.

Among the available approaches for processing refractory gold ores, bacterial oxidation has gained considerable attention in recent years, particularly for sulfide-rich flotation concentrates (Liu et al., 2004; Yang et al., 2002). The increasing application of this technology is primarily attributed to its high degree of desulfurization efficiency, environmentally favorable characteristics, and relatively low operational costs compared to conventional thermal or pressure oxidation methods (Tributsch, 2001; Biletsky et al., 2019). These advantages largely compensate for the stringent operational requirements associated with bio-oxidation, which arise from the need to maintain optimal conditions for microbial activity, including controlled temperature, pH, redox potential, and nutrient availability, all of which are essential for sustaining microbial adaptation and metabolic efficiency. Moreover, bacterial consortia demonstrate selective oxidation of sulfide minerals, which contributes to the structural weakening of the ore matrix and enhances subsequent gold exposure during cyanidation.

Figure 2 presents the powder X-ray diffraction pattern of the bio-oxidized product (bio-cake). The corresponding semi-quantitative mineralogical composition, obtained through Rietveld refinement of the diffraction data, is summarized in Table 2. These results provide important insights into the extent of sulfide transformation, the formation of secondary phases such as jarosite, and the residual mineral assemblages remaining after bio-oxidation treatment, which collectively influence downstream gold recovery performance.

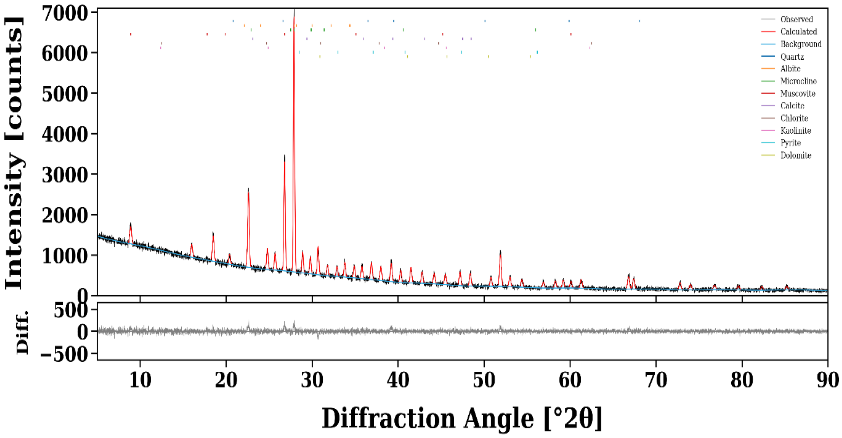


Figure 2. Powder diffractogram of bioke sample.

Table 2. Mineralogical analysis of biokeek sample.

| Mineral | Contents, % |
|---|---|
| Pyrite | 2.1 |
| Quartz | 26,4 |
| Muscovite | 21.5 |
| Albit | 11.3 |
| Chlorite | 10.5 |
| Carbonaceous matter | 12,8 |
| Other (anorthite, calcite, etc.) | ~15,1 |

Bio-oxidation of the flotation concentrate achieved a high degree of desulfurization, exceeding 90%, indicating effective microbial decomposition of sulfide minerals. However, despite this substantial removal of sulfur-bearing phases, gold recovery during subsequent sorption cyanidation remained unsatisfactory. This discrepancy can be attributed primarily to the elevated content of carbonaceous matter in the resulting bio-cake, which continues to exert a pronounced preg-robbing effect by adsorbing dissolved gold–cyanide complexes and thereby reducing the efficiency of gold recovery.

In order to mitigate the adverse influence of carbonaceous material, oxidative roasting was considered as a further pretreatment step. This approach is aimed at thermally deactivating or removing reactive carbon phases that are responsible for gold adsorption losses. Accordingly, roasting experiments were carried out in a muffle furnace at a temperature range of 500–550°C for a duration of 3 hours, with the process continued until a constant mass of the calcined residue was achieved, indicating completion of thermal transformations.

The phase composition of the roasted product was subsequently investigated by powder X-ray diffraction (XRD). The diffraction pattern obtained is presented in Figure 3, while the semi-quantitative mineral composition, determined through Rietveld refinement of the XRD data, is summarized in Table 3. These results provide insight into the mineralogical transformations induced by thermal treatment and the effectiveness of carbon removal under oxidative conditions.

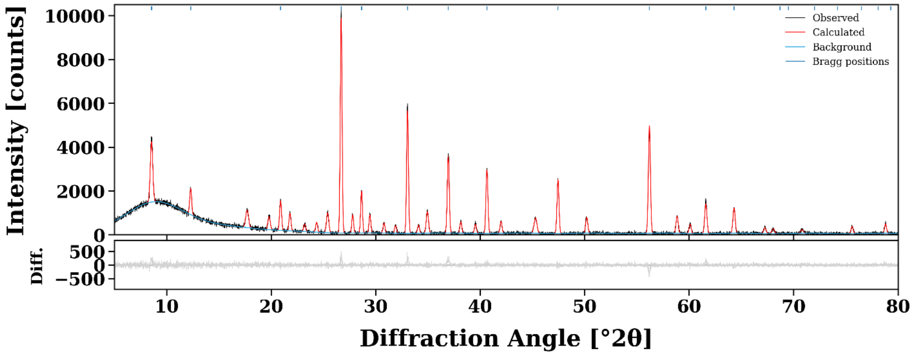


Figure 3. Powder diffractogram of the roasted sample.

Table 3. Mineralogical analysis of the roasted sample.

| **Mineral** | **Contents, %** |
|---|---|
| Quartz | 36.4 |
| Muscovite | 29.0 |
| Albit | 13.6 |
| Hematite | 3.4 |
| Maghemite | 1.0 |
| Carbonaceous matter | 0,6 |
| Other (anorthite, calcite, etc.) | ~16 |

The results show that the sulfide minerals have been completely oxidized. The carbon content is 0.6%, and the carbon is likely in the form of graphite, whose combustion temperature significantly exceeds the temperature of oxidative roasting. Iron has been oxidized mainly to hematite, with some iron present in the form of maghemite. Although oxidative roasting is more costly from an economic point of view, it ensured a high degree of desulfurization and decarbonization. Nevertheless, gold recovery in subsequent sorption cyanidation did not exceed 75%. To investigate the reasons for the low gold recovery, the sample was subjected to additional studies.

Scanning electron microscopy of the roasted sample revealed the presence of nanoscale gold particles (Fig. 4, Table 4).

As shown in Figure 4, gold particles with sizes of approximately 100 nm and below were detected within the pyrrhotite matrix. According to spectral analysis, particularly Spectra 83 and 85, these nanophase inclusions correspond to elemental gold. In addition, Spectra 83 and 86 were obtained from the host mineral, which is compositionally consistent with pyrrhotite based on the characteristic sulfur-to-iron ratio. These observations indicate that a significant portion of gold remains physically encapsulated within sulfide minerals due to incomplete oxidation of iron sulfides during muffle furnace treatment. The periodic mixing conditions employed during thermal processing are insufficient to ensure uniform oxygen diffusion and complete sulfide decomposition, resulting in under-oxidized pyrite–pyrrhotite assemblages and, consequently, the preservation of refractory gold phases.

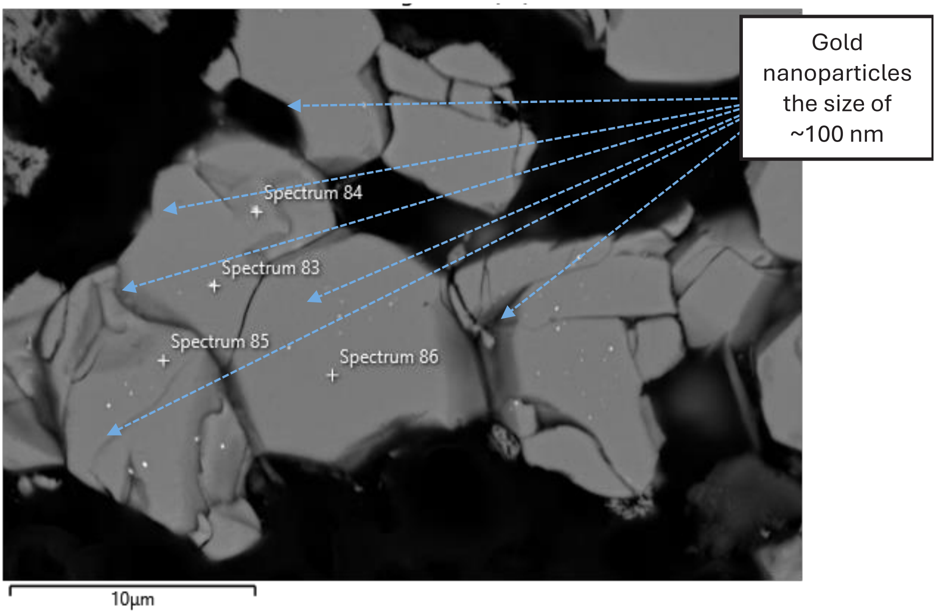


Figure 4. Gold nanoparticles in pyrrhotite.

Table 4. Content of elements in measurement points.

| | S | Fe | Au |
|---|---|---|---|
| Spectrum 83 | 28,4% | 42,8% | 28,8% |
| Spectrum 84 | 39,2% | 60,8% | - |
| Spectrum 85 | 27,2% | 38,2% | 34,7% |
| Spectrum 86 | 39,4% | 60,6% | - |

The presence of nanoscale gold inclusions strongly suggests that conventional comminution and roasting techniques alone are inadequate for full liberation of precious metals from the sulfide matrix. To effectively access and recover such finely disseminated gold, it is necessary to employ advanced ultrafine grinding strategies capable of reducing particle size to the submicron or even nanoscale range, thereby increasing the exposure of encapsulated gold surfaces.

In industrial practice, preliminary size reduction of ore material can be achieved through controlled blasting operations in open-pit mining, followed by staged comminution using dry grinding systems such as two-chamber ball mill–separator circuits. However, to reach the required liberation size for refractory ores, these conventional methods must be supplemented with specialized ultrafine grinding technologies, which provide significantly higher energy input and improved particle breakage efficiency.

Further experimental investigations were carried out using high-temperature oxygen–lime treatment (OLT) of flotation concentrates. A distinctive feature of this process is the pre-treatment of the material to a particle size of approximately 20 μm, followed by oxidative leaching in the presence of oxygen and lime at a temperature of 75–80°C under atmospheric pressure conditions. This regime promotes the oxidative decomposition of sulfide minerals, enhances permeability of the mineral matrix, and facilitates the release of encapsulated gold. The corresponding results obtained after OLT processing of the flotation concentrate are presented in Figure 5 and Table 5, demonstrating the effectiveness of the proposed approach in improving sulfide oxidation and gold liberation.

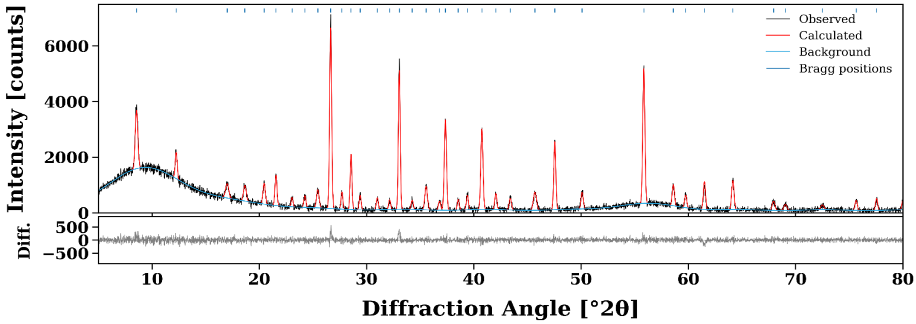


Figure 5. Powder diffractogram of the flotation concentrate sample after the OLT process.

Table 5. Mineralogical analysis of the flotation concentrate sample after the OLT process.

| Mineral | Contents, % |
|---|---|
| Quartz | 18.2 |
| Pyrite | 19.0 |
| Muscovite | 31.4 |
| Albit | 3.8 |
| Chlorite | 6.4 |
| Bassanite | 0.8 |
| Jarosite | 3.9 |
| Gypsum | 1.0 |
| Anorthite | 1.4 |
| Amorphous part | 14.2 |

After the OLT process, the flotation concentrate still exhibits a relatively high residual content of pyrite together with significant amounts of carbonaceous matter. Although partial oxidation of pyrite is evident, the process remains incomplete and is accompanied by the formation of secondary iron-bearing phases, predominantly jarosite. The occurrence and accumulation of jarosite are particularly unfavorable from a metallurgical standpoint, as it contributes to surface passivation of sulfide minerals, restricts further oxygen diffusion through pore and grain boundaries, and thereby inhibits the continuation of pyrite oxidation under the applied treatment conditions. In addition, the formation of such secondary phases may alter the surface electrochemical properties of the particles, further reducing their reactivity in subsequent leaching stages.

Microscopic examination of the treated sample at 1200× magnification (Figure 6) clearly reveals the presence of finely dispersed carbonaceous material embedded within the mineral matrix. The majority of this carbon occurs in an amorphous form, lacking a well-defined crystalline structure and being uniformly distributed throughout the concentrate at micro- and nanoscale levels. Such amorphous carbon is highly reactive in hydrometallurgical systems and is widely recognized for its strong preg-robbing behavior. In particular, it can effectively and selectively adsorb dissolved gold complexes, especially those formed with cyanide ions during subsequent leaching stages, due to its high specific surface area and surface functional activity.

This phenomenon significantly reduces the overall efficiency of gold recovery, as a portion of the solubilized gold is continuously removed from the pregnant leach solution and re-adsorbed onto carbon surfaces rather than remaining in solution for downstream recovery processes such as activated carbon adsorption or zinc cementation. Consequently, the combined presence of partially oxidized sulfides, jarosite coatings, and highly reactive carbonaceous matter creates a complex and dynamically evolving mineralogical environment that continues to limit the effectiveness of conventional oxidative pretreatment and cyanidation-based extraction processes, thereby necessitating more advanced integrated processing strategies.

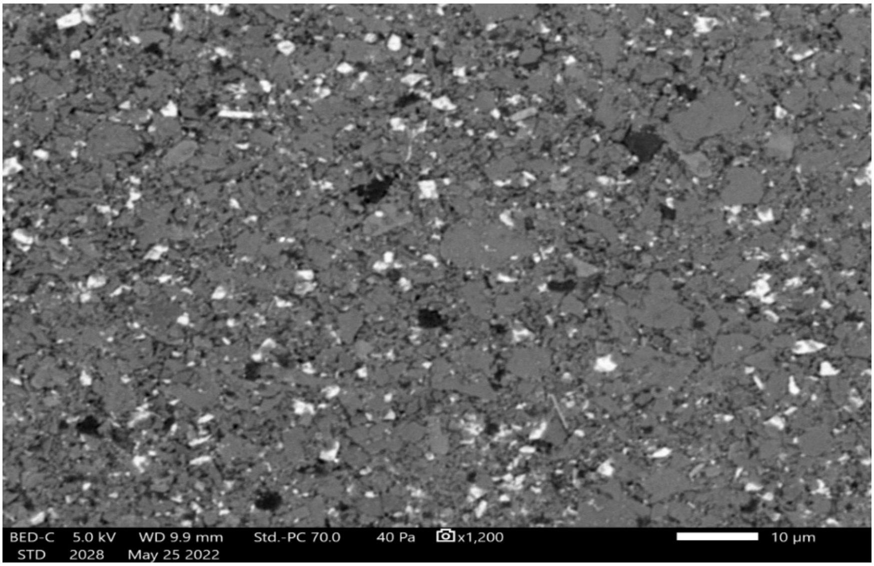


Figure 6. Surface of the sample "Crushed flotation concentrate after the OLT process" at 1200x magnification, dark particles represent carbon.

The elevated content of pyrite and carbonaceous matter classifies the flotation concentrate, even after OLT treatment, as a double-refractory gold-bearing material. Although ultrafine grinding to a particle size of approximately 20 µm can significantly improve the exposure, liberation, and accessibility of nanoscale gold by increasing the specific surface area and enhancing the contact between the leaching solution and mineral phases, this benefit alone remains insufficient for achieving consistently high gold recovery rates under industrial cyanidation conditions. In addition, the presence of finely disseminated gold locked within sulfide matrices, particularly within pyrite and associated gangue minerals, further limits complete liberation even at advanced degrees of comminution, thereby maintaining a significant fraction of unrecoverable gold in the solid phase.

At the same time, the carbonaceous matter exerts a critical negative influence on the overall hydrometallurgical performance of the process. It exhibits a strong preg - robbing effect, characterized by the competitive adsorption of dissolved gold–cyanide complexes onto active carbon sites distributed within the ore matrix. This phenomenon not only reduces the concentration of gold in the pregnant leach solution but also disrupts the thermodynamic equilibrium of dissolution–adsorption processes, significantly decreasing the efficiency of downstream recovery stages such as adsorption onto activated carbon, ion-exchange resins, or zinc cementation. As a result, a considerable portion of the dissolved gold is irreversibly transferred to the tailings stream, thereby lowering the overall process yield.

Furthermore, the interaction between liberated gold species and residual or partially oxidized sulfide minerals may contribute to secondary encapsulation and surface passivation effects, which further complicate mass transfer kinetics during cyanidation. Therefore, despite the mechanical advantages provided by fine and ultrafine grinding, the overall process efficiency remains strongly constrained by the chemical reactivity, surface properties, and adsorption behavior of carbonaceous phases. This confirms that effective processing of such double-refractory ores requires not only physical liberation strategies but also targeted chemical, oxidative, or thermal pre-treatment methods aimed at deactivating carbonaceous matter prior to cyanidation and improving overall gold recoverability.

Comparative results of gold extraction using various methods of its opening are shown in Table 6.

Table 6. Comparative results of gold extraction.

| Processing method | Gold extraction, % |
|---|---|
| Cyanidation only | ≤50 |
| After the OLT process | ~65 |
| After biooxidation | ~70 |
| After oxidative roasting | 72–75 |

**Conclusion.** The flotation concentrates obtained from the Auminz–Amantay ore field can be classified as double refractory gold ores, exhibiting both physical encapsulation and chemical refractoriness. Despite the application of advanced processing technologies such as oxygen-lift leaching (OLT), BIOX bio-oxidation, and conventional roasting, the overall gold recovery remains limited and typically does not exceed 75%. This indicates that the current processing routes are insufficient to fully overcome the complex mineralogical barriers inherent in the ore.

The primary factors responsible for the low extraction efficiency are associated with the complex distribution and chemical behavior of gold within the ore matrix. First, gold predominantly occurs in nanoscale and submicroscopic forms, which are finely disseminated and structurally enclosed within silicate and sulfide gangue minerals. Such occurrences significantly restrict reagent accessibility and limit the effectiveness of both chemical leaching and oxidative pretreatment methods. Second, the presence of carbonaceous matter leads to a pronounced preg-robbing effect, whereby dissolved gold complexes are re-adsorbed onto organic carbon surfaces, resulting in substantial losses during cyanidation. Third, the formation of secondary oxidation products, including jarosite and bassanite, creates additional diffusion barriers and passivation layers that hinder the penetration of oxidizing agents and further suppress gold liberation.

In order to enhance overall gold recovery, it is necessary to develop and implement integrated and synergistic processing strategies rather than relying on single-stage treatment schemes. In particular, combined approaches involving controlled oxidative roasting with prior or simultaneous carbon deactivation are required to eliminate the preg-robbing capacity of organic matter. This should be followed by the optimization of cyanidation parameters, including reagent concentration, pH control, and oxygen supply, to maximize gold dissolution kinetics. Furthermore, the application of advanced sorption–desorption technologies, such as carbon-in-leach (CIL) and carbon-in-pulp (CIP) systems, is recommended to improve gold capture efficiency and minimize losses in solution.

Overall, a multi-stage hybrid processing route that integrates thermal, chemical, and adsorption-based technologies appears to be the most promising direction for achieving higher gold recoveries from such complex double refractory ores.

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