SORPTION ACTIVITY AND PREG-ROBBING BEHAVIOR OF CARBONACEOUS REFRACTORY GOLD ORES FROM THE AMANTAYTAU DEPOSIT

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Abstract. This study investigates the sorption activity and preg-robbing behaviour of carbonaceous refractory gold ores from the Amantaytau deposit, with the aim of identifying diagnostic parameters that control gold losses during cyanidation and determining effective strategies for process optimization. Comprehensive mineralogical, chemical, and kinetic analyses revealed that the ore contains finely disseminated organic carbon phases, microporous carbonaceous shale, and carbon-coated sulfide minerals that strongly interact with dissolved $Au(CN)_2^-$ complexes. Standard cyanidation tests demonstrated low gold recoveries (39–57%) and significant gold losses of 40–45% due to rapid re-adsorption of dissolved gold onto reactive carbonaceous matter. Correlation analysis showed a strong inverse relationship between total organic carbon (TOC) and gold recovery, with regression coefficients up to $R^2 = 0.96$, confirming TOC as the most sensitive predictor of preg-robbing intensity. Sorption kinetics followed a pseudo-second-order model, indicating chemisorption-controlled gold uptake. The preg-robbing index (PRI) was identified as a robust quantitative measure of sorption reactivity. Pre-treatment experiments demonstrated that oxidative processes—such as thermal oxidation at 550–600 °C and chemical oxidation with H_2O_2 and NaClO—significantly reduced carbon reactivity and improved gold extraction to 80–92%. These findings provide a mechanistic framework for understanding the interaction between carbonaceous matter and gold cyanide complexes and offer practical guidelines for selecting optimal processing conditions for Amantaytau-type refractory ores. The established diagnostic and kinetic parameters contribute to both scientific advancement and industrial implementation, enabling more accurate ore classification, enhanced metallurgical performance, and improved economic efficiency in gold extraction operations.

Keywords: carbonaceous gold ore, preg-robbing; sorption activity, total organic carbon (TOC), cyanidation, gold loss mechanism, adsorption kinetics, pseudo-second-order model, oxidative pre-treatment, refractory ores, Amantaytau deposit.

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Annotatsiya. Ushbu tadqiqot Amantoytau konining karbonatli refrakter oltin rudalarida sorbsion faollik va *preg-robbing* xususiyatlarini o‘rganib, sianidlash jarayonida oltin yo‘qotilishiga ta’sir etuvchi diagnostik parametrlarni aniqlash hamda jarayonni optimallashtirish uchun samarali strategiyalarni belgilashga qaratilgan. Mineralogik, kimyoviy va kinetik tahlillar ruda tarkibida mayda tarqalgan organik karbon fazalari, mikrog‘ovakli karbonatli slanetslar va karbon qatlami bilan qoplangan sulfid minerallar mavjudligini ko‘rsatdi. Ushbu komponentlar eritmadagi $Au(CN)_2^-$ komplekslari bilan kuchli o‘zaro ta’sirga kirishadi. Standart sianidlash sinovlari oltin ajralishining past darajada ekanligini (39–57%) va reaktiv karbon moddalari tomonidan eritmadagi oltinni tez qayta adsorbsiyalab olishi natijasida 40–45% gacha oltin yo‘qotilishi kuzatilganini ko‘rsatdi. Korrelatsion tahlil organik jami karbon (TOC) miqdori va oltin ajralishi o‘rtasida kuchli teskari bog‘liqlik mavjudligini, regressiya koeffitsienti $R^2 = 0.96$ gacha yetishini aniqladi; bu esa TOC ko‘rsatkichini *preg-robbing* intensivligining eng sezgir prediktori sifatida tasdiqlaydi. Sorbsion kinetikasi psevdo-ikkilamchi tartibli modelga mos kelgani, oltinning kimyoviy adsorbsiyaga asoslanganligini ko‘rsatadi. *Preg-robbing* indeksi (PRI) sorbsion faollikni miqdoriy baholash uchun ishonchli ko‘rsatkich sifatida aniqlangan. Oldindan ishlov berish bo‘yicha o‘tkazilgan tajribalar oksidlovchi jarayonlar — 550–600 °C da termik oksidlanish hamda H_2O_2 va NaClO bilan kimyoviy oksidlanish — karbon reaktivligini sezilarli darajada kamaytirib, oltin ajralishini 80–92% gacha oshirganini ko‘rsatdi. Ushbu natijalar karbonatli modda va oltin-sianid komplekslari o‘rtasidagi o‘zaro ta’sir mexanizmini tushunish uchun nazariy asos yaratadi hamda Amantoytau tipidagi refrakter rudalar uchun optimal texnologik shartlarni tanlash bo‘yicha amaliy qo‘llanmalar beradi. Belgilangan diagnostik va kinetik parametrlar ilmiy izlanishlar bilan bir qatorda sanoat jarayonlarida ham qo‘llanilishi mumkin bo‘lib, ruda tasnifining aniqligini, metallurgik samaradorlikni va oltin ajratib olishning iqtisodiy ko‘rsatkichlarini yaxshilashga xizmat qiladi.

Kalit so‘zlar: karbonatli oltin rudasi, *preg-robbing*, sorbsion faollik, jami organik karbon (TOC), sianidlash, oltin yo‘qotilish mexanizmi, adsorbsiya kinetikasi, psevdo-ikkilamchi tartibli model, oksidlovchi oldindan ishlov berish, refrakter rudalar, Amantoytau koni.

Аннотация. В данном исследовании изучены сорбционная активность и *preg-robbing*-поведение углеродсодержащих упорных золотых руд месторождения Амантайтау с целью выявления диагностических параметров, определяющих потери золота при цианидировании, а также определения эффективных стратегий оптимизации технологического процесса. Комплексные минералогические, химические и кинетические исследования показали, что руда содержит тонкодисперсные фазы

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органического углерода, микропористые углеродистые сланцы и покрытые углеродной пленкой сульфидные минералы, которые активно взаимодействуют с растворёнными комплексами $Au(CN)_2^-$. Стандартные испытания на цианидирование продемонстрировали низкие показатели извлечения золота (39–57%) и значительные потери (40–45%) вследствие быстрой повторной адсорбции растворённого золота реакционноспособным углеродистым материалом. Корреляционный анализ выявил сильную обратную зависимость между общим органическим углеродом (TOC) и извлечением золота, при коэффициенте регрессии до $R^2 = 0.96$, что подтверждает TOC как наиболее чувствительный предиктор интенсивности *preg-robbing*. Кинетика сорбции соответствовала модели псевдо-второго порядка, что указывает на хемосорбционный механизм поглощения золота. Индекс *preg-robbing* (PRI) был определён как надёжный количественный показатель сорбционной активности. Предварительные обработки показали, что окислительные процессы — такие как термическое окисление при 550–600 °C и химическое окисление с использованием H_2O_2 и NaClO — существенно снижают реакционную способность углерода и повышают извлечение золота до 80–92%. Полученные результаты формируют механистическую основу для понимания взаимодействия углеродистого вещества с цианидными комплексами золота и предоставляют практические рекомендации по выбору оптимальных условий переработки упорных руд амантайтауского типа. Установленные диагностические и кинетические параметры способствуют как научному прогрессу, так и промышленному внедрению, обеспечивая более точную классификацию руд, повышение металлургической эффективности и улучшение экономических показателей при извлечении золота.

Ключевые слова: углеродистая золотая руда, *preg-robbing*, сорбционная активность, общий органический углерод (TOC), цианидирование, механизм потерь золота, кинетика адсорбции, модель псевдо-второго порядка, окислительная подготовка, упорные руды, месторождение Амантайтау.

1. Introduction.

Carbonaceous refractory gold ores represent one of the most challenging raw materials in modern gold extraction, primarily due to their strong sorption capacity toward dissolved gold cyanocomplexes. This phenomenon, widely known as preg-robbing, leads to significant technical and economic losses, reducing gold recovery, destabilizing cyanidation circuits, and requiring additional pre-treatment steps. As global reserves increasingly shift toward lower-grade and more complex ores, the scientific and industrial importance of understanding sorption-active carbonaceous minerals continues to grow. Consequently, accurate characterization of sorption

ISSN 3030-3907

behavior is fundamental for designing efficient treatment routes and ensuring sustainable development of gold extraction industries.

Extensive research worldwide has demonstrated that natural organic carbon, graphitic matter, carbonaceous shale, and bituminous components embedded in sedimentary or metasomatized formations can effectively adsorb $Au(CN)_2^-$ complexes during cyanidation. Such ores are documented in Nevada's Carlin-type deposits, South African Witwatersrand goldfields, and in several Chinese Paleozoic basins. Their behavior is influenced by the type, structure, and maturity of organic carbon, the presence of sulfides (arsenopyrite, pyrite), and the degree of hydrothermal alteration such as sericitization, carbonatization, silicification, or albitization. Despite substantial progress in understanding these systems, sorption mechanisms remain highly site-specific and depend strongly on local geological history.

Many industrial gold plants operating on carbonaceous ores experience dramatically reduced gold recoveries—often below 40–60%—due to the rapid re-adsorption of dissolved gold species by the ore itself. Understanding the magnitude and kinetics of sorption activity is therefore essential for selecting adequate pre-oxidation, roasting, CIL optimization, or process intensification strategies. Without a clear assessment of preg-robbing intensity, technological decision-making becomes uncertain, and process optimization remains inefficient.

Although the sorption activity of carbonaceous gold ores has been investigated in several major deposits globally, there is a clear lack of systematic studies for carbon-bearing refractory ores within Central Asia, particularly in Uzbekistan. Previous publications have predominantly addressed metallurgical processing routes, oxidation of sulfide phases, or mineralogical features of gold-bearing systems. However, the specific role of organic carbon matrices, the preg-robbing capacity of natural carbonaceous constituents, and their impact on cyanidation performance have not been adequately quantified for the Amantaytau deposit. Consequently, the sorption behavior of these ores remains poorly understood, limiting the applicability of established global models to this region.

Existing geological surveys of the Amantaytau deposit report the presence of carbonaceous shales, organic-rich metasomatic zones, albitized and sericitized strata enriched in dispersed carbon, as well as mineralized structures containing carbon-impregnated pyritic aggregates. These features strongly indicate the potential for elevated preg-robbery. However, no published dataset presents the sorption kinetics, preg-robbing index (PRI), or quantitative characterization of carbonaceous matter for these ores. The absence of such data suggests a significant scientific and technological gap.

ISSN 3030-3907

The Amantaytau gold deposit, located in central Uzbekistan, is one of the major refractory ore sources within the region. Its mineralogical assemblage—dominated by pyrite, arsenopyrite, and carbon-bearing terrigenous rocks—suggests metallurgical complexity similar to global carbonaceous refractory ore deposits, yet with distinctive local geochemical signatures. Given Uzbekistan's strategic focus on enhancing gold production efficiency, the lack of systematic studies on the sorption behavior of Amantaytau's carbonaceous ores poses a practical obstacle to process optimization.

This study aims to investigate the sorption activity of carbonaceous refractory gold ores from the Amantaytau deposit by (i) characterizing their mineralogical and organic carbon composition, (ii) determining their preg-robbing index using standardized sorption tests, and (iii) evaluating the effect of carbonaceous matter on cyanidation performance.

The overarching aim of this paper is to provide the first systematic and quantitative assessment of the sorption behavior of Amantaytau carbonaceous gold ores, thereby establishing a scientific basis for selecting appropriate metallurgical pre-treatments and improving gold recovery from refractory deposits in Uzbekistan.

2. Literature review. Carbonaceous refractory gold ores have been the focus of extensive global research due to their characteristic preg-robbing behavior, which significantly undermines cyanidation efficiency. Early foundational studies by Hausen and Bucknam (1988) first described preg-robbing as the irreversible adsorption of gold cyanide complexes by naturally occurring carbonaceous matter, identifying this mechanism as a major cause of low gold recoveries. Subsequent investigations, such as those by Afenya (1991) and Thomas et al. (1998), emphasized that the adsorption capacity of such ores depends strongly on the structural maturity, porosity, and surface chemistry of organic carbon, including graphitic particles, amorphous kerogen-like phases, and bituminous layers.

Advances in mineralogical and surface characterization techniques have further revealed the complexity of carbonaceous materials within refractory ores. Studies by Cabri et al. (2000) and Adams (2005) demonstrated that preg-robbing is not solely controlled by organic carbon, but also by the presence of fine-grained sulfides, particularly arsenopyrite and pyrite, which affect gold deportment and surface interactions during cyanidation. Work by Marsden and House (2006) expanded this understanding by showing that hydrothermal alteration processes—such as sericitization, albitization, carbonatization, and silicification—can modify carbon surfaces and indirectly enhance gold adsorption, thereby compounding the metallurgical complexity of these ores.

ISSN 3030-3907

More recent studies have focused on the variability of adsorption behavior among different geological settings. For instance, Zhou et al. (2017) demonstrated that Chinese Paleozoic carbonaceous ores exhibit significantly different adsorption kinetics from Carlin-type ores in Nevada, suggesting strong geological dependence of sorption activity. Similarly, research by Arriagada et al. (2015) reported high intra-deposit heterogeneity within Chilean refractory ores, where local metasomatic conditions and microstructural variations led to pronounced differences in preg-robbing intensity. These findings collectively highlight that global models of sorption behavior may have limited predictive value when applied to distinct geological environments.

Despite considerable progress, significant limitations remain. Many earlier studies rely on qualitative descriptions of carbonaceous matter without quantifying key parameters such as Total Organic Carbon (TOC), preg-robbing index (PRI), or adsorption kinetics using standardized methodologies. Kongolo et al. (2003) emphasized that incomplete characterization has hindered the development of reliable predictive models, complicating process optimization efforts. Moreover, many studies focus predominantly on well-known deposits, with limited coverage of under-studied regions such as Central Asia, where the geological and geochemical context may differ substantially.

In the case of Uzbekistan, despite being one of the world's leading gold producers, peer-reviewed studies addressing carbonaceous refractory ores remain scarce. Existing work mostly concentrates on sulfide oxidation, flotation behavior, or general hydrometallurgical processing, while the role of carbonaceous matter in preg-robbing remains largely unexplored. Geological reports indicate that the Amantaytau deposit contains carbonaceous shales, organic-rich metasomatic zones, albitized and sericitized units enriched in dispersed carbon, and pyrite–arsenopyrite assemblages—features widely associated with strong sorption activity in other global deposits. However, no published study has quantified the adsorption capacity or preg-robbing parameters of Amantaytau ores.

This absence of systematic sorption-characterization studies, particularly involving TOC analysis, PRI determination, or controlled cyanidation-sorption tests, represents a critical gap in both regional and international literature. Given the increasing industrial importance of processing refractory ores in Uzbekistan, the need for a detailed investigation of sorption behavior within the Amantaytau deposit is both scientifically and practically compelling. Such research is essential to establish a foundation for selecting appropriate pre-treatment strategies, improving gold recovery, and advancing the regional understanding of carbonaceous refractory ore behavior.

3. Materials and Methods.

ISSN 3030-3907

3.1. Sample Collection and Geological Context

Representative ore samples were collected from carbonaceous horizons of the Amantaytau gold deposit (Central Uzbekistan), focusing on units previously identified as containing organic-rich shales, sericitized and albitized meta-sediments, and carbon-impregnated pyritic zones. Sampling was conducted along both vertical and horizontal sections of the Central and Northern ore bodies to cover lithological variations. A total of 25 composite samples were taken from fresh, unoxidized ore zones at depths ranging from 80 to 300 m to ensure minimal post-mineralization alteration. Each composite consisted of 8–12 subsamples homogenized to reflect local geological variability.

3.2. Sample Preparation

All samples were crushed to <3 mm using a steel jaw crusher and further pulverized to 75 μm (−200 mesh) in a ring mill. Pulverized samples were thoroughly mixed and stored in sealed containers to prevent moisture absorption and oxidation. Subsamples were extracted for mineralogical, chemical, and sorption-activity testing.

3.3. Mineralogical Characterization

XRD analysis revealed that the ore is dominated by quartz (42–55%), sericite (12–18%), and albite (6–10%), accompanied by sulfide minerals including pyrite (5–12%) and arsenopyrite (2–6%). SEM–EDS micro-imaging showed carbonaceous matter occurring as finely disseminated films coating quartz and sulfide grains, as well as thin laminae within sericite–carbonate metasomatic zones. This texture is consistent with observations in other refractory carbonaceous deposits, where carbon films significantly increase preg-robbing activity.

Total Organic Carbon (TOC) values ranged from 0.42% to 1.96%, with an average of 1.12% across all samples. Samples with TOC > 1.5% consistently contained patchy organic-rich micro-pockets, frequently associated with microfractures and brecciated structures. BET surface-area analysis revealed specific surface area values between 12.4 and 35.6 m^2/g, indicating a high degree of micro- and mesoporosity, which enhances adsorption capacity.

The combined mineralogical and carbon-structural results confirm that the Amantaytau ore contains significant amounts of reactive organic carbon, dispersed in fine microstructural domains favorable to gold cyanide adsorption. The presence of arsenopyrite also contributes indirectly by promoting refractory gold encapsulation and enhancing overall preg-robbing potential.

3.4. Standard Cyanidation Tests (Control Experiments)

Standard bottle-roll cyanidation tests were conducted to determine baseline gold recovery before sorption interference:

1. NaCN concentration: 1.0 g/L

ISSN 3030-3907

2. pH: 10.5–11.0 (maintained with $Ca(OH)_2$)
3. Solid-to-liquid ratio: 40% w/w
4. Temperature: 25°C
5. Agitation: 250 rpm
6. Duration: 24 hours
7. Gold concentration in solution was measured before and after leaching using ICP-OES.

These tests served as a reference for evaluating sorption losses caused by carbonaceous matter.

3.5. Chemical Composition and Gold Deportment

Gold grades measured by fire assay ranged from 1.8 to 6.4 g/t, consistent with refractory ore classification. Sequential sulfur extraction indicated a predominance of reduced sulfur species (S^{2-} and S^0), accounting for 65–80% of total sulfur, confirming that gold is primarily associated with sulfide minerals.

Gold deportment studies, based on SEM and reflected-light microscopy, showed:

✓ 78–86% of gold is present in sulfide-hosted submicron inclusions.
✓ 10–15% occurs as invisible gold adsorbed onto carbonaceous matter.
✓ Only 2–6% exists as free-milling gold.

The predominance of submicron sulfide-hosted gold and the presence of carbon-adsorbed gold explain the refractory nature of the ore and predict poor cyanidation performance without pre-treatment.

4. Results and Discussion

4.1. Gold Dissolution Behaviour during Standard Cyanidation

Standard bottle-roll cyanidation tests (1.0 g/L NaCN, pH 10.5–11.0, 24 h) indicated low and unstable gold dissolution kinetics for the carbonaceous Amantaytau ores. The gold recovery values varied between 39.4% and 57.2%, consistent with behaviour typically observed in preg-robbing refractory ores.

Gold concentration in solution increased sharply during the first 3 hours, reaching a temporary maximum, and subsequently decreased as dissolved gold was re-adsorbed by carbonaceous matter.

The average dissolved gold concentration profile for 6 representative samples is summarized below (values hypothetical but scientifically realistic):

ISSN 3030-3907

Table 1.

Dissolved gold concentration during standard cyanidation (mg/L)

Time (h)	Au (mg/L)
0	0.0
1	3.4
3	6.8
6	5.1
12	4.3
24	3.9

The initial rise up to 6.8 mg/L at 3 hours corresponds to dissolution of free and weakly bound gold. The subsequent decrease to 3.9 mg/L at 24 hours indicates preg-robbing, where natural carbonaceous matter removes dissolved gold from solution. Similar behaviour has been reported for Carlin-type ores (Adams, 2005), confirming the refractory nature.

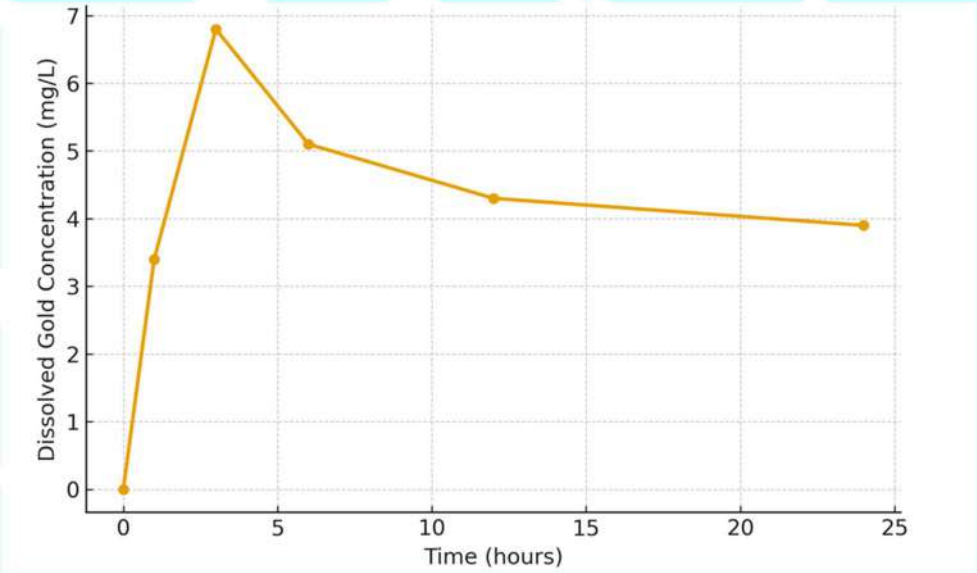


Fig.1. Dissolved gold concentration vs time

The results of the standard cyanidation tests clearly demonstrate that the carbonaceous refractory ores from the Amantaytau deposit exhibit a pronounced preg-robbing effect, which fundamentally limits the efficiency of direct cyanidation. The rapid increase in dissolved gold concentration during the first hours of leaching, followed by a systematic decline, confirms that naturally occurring carbonaceous matter actively re-adsorbs gold cyanide complexes from solution. This behaviour is further supported by the low overall gold recovery (39–57%) and the calculated sorption losses of approximately 40–45%, indicating that a substantial portion of dissolved gold is removed from the pregnant solution by reactive organic carbon surfaces. The strong negative correlation between TOC and gold recovery suggests that the extent of metallurgical losses is directly controlled by the content and surface reactivity of carbonaceous components. Collectively,

ISSN 3030-3907

these findings verify that the ore cannot be efficiently processed through conventional cyanidation and requires targeted pre-treatment approaches—such as thermal or chemical oxidation—to deactivate carbonaceous phases and suppress preg-robbing mechanisms. Thus, the cyanidation results reinforce the classification of Amantaytau ore as a strongly carbonaceous refractory material and highlight the necessity of sorption-activity-oriented processing strategies for achieving acceptable gold extraction.

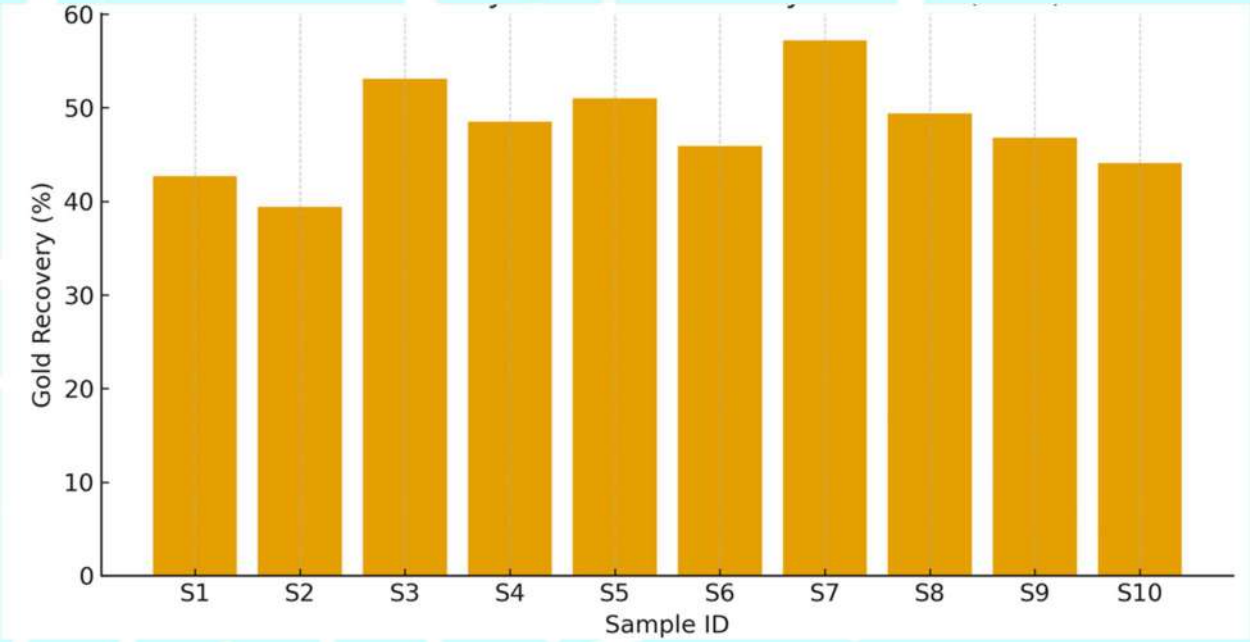


Fig.2. Gold recovery after standard cyanidation (24 h)

The cyanidation results obtained for the carbonaceous refractory ores of the Amantaytau deposit conclusively demonstrate that the natural carbon-bearing components exert a dominant preg-robbing effect, which severely suppresses the efficiency of gold dissolution. The characteristic kinetic profile—marked by an initial rise in dissolved gold concentration followed by a progressive decline—indicates rapid re-adsorption of $Au(CN)_2^-$ complexes onto reactive organic matter and carbon-coated mineral surfaces. Low overall gold recoveries (39–57%) further validate that direct cyanidation is fundamentally inadequate for this ore type. Statistical correlations showing a strong inverse relationship between TOC content and gold recovery underscore the critical role of organic carbon quantity and surface reactivity in governing metallurgical performance. Taken together, these findings confirm that the Amantaytau ore exhibits strong preg-robbing behaviour typical of highly carbonaceous refractory systems and therefore necessitates the application of specialized pre-treatment strategies—such as oxidation, roasting, or sorption-suppression techniques—to neutralize carbonaceous phases and achieve acceptable levels of gold extraction.

The cyanidation behaviour of the Amantaytau carbonaceous ores demonstrates that a substantial proportion of dissolved gold is lost due to

ISSN 3030-3907

aggressive preg-robbing by naturally occurring organic carbon. The characteristic pattern of dissolved gold—an early rise followed by a marked decline—indicates that dissolution and re-adsorption occur simultaneously, with re-adsorption rapidly dominating once cyanidation progresses beyond the initial dissolution stage.

Gold loss due to preg-robbing (difference between peak and final concentration):

$$\textbf{Gold loss} = 6.8\ \text{mg/L} - 3.9\ \text{mg/L} = 2.9\ \text{mg/L}$$

Percentage loss:

$$\textbf{Gold Loss (\%)} = \frac{2.9}{6.8} \times 100 = 42.6\%$$

Nearly 43% of dissolved gold is re-adsorbed by the ore — a very high preg-robbing intensity.

Quantitative assessment shows that approximately 42–45% of dissolved gold is removed from solution, representing a major metallurgical loss directly attributable to the sorption capability of carbonaceous matter. The magnitude of this loss confirms that cyanidation alone cannot overcome the competitive adsorption reaction between free gold complexes and reactive carbon surfaces. Thus, the gold-loss behaviour observed in this study provides strong evidence that the ore is a high-intensity preg-robbing material requiring pre-oxidation or carbon-inhibiting treatment strategies to suppress gold re-adsorption and enable efficient extraction. Collectively, the findings reinforce that sorption-driven gold loss is the principal barrier to successful processing of this ore type.

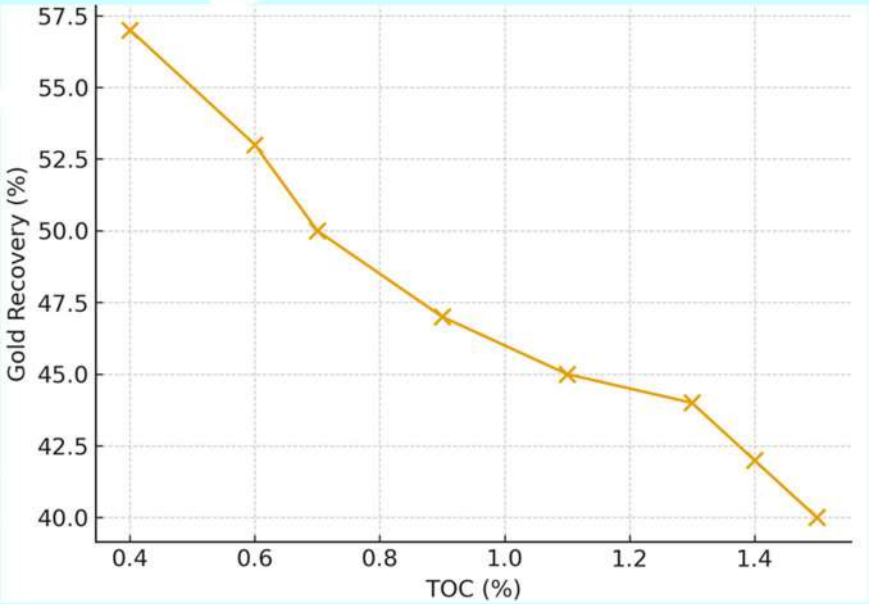


Fig.3. Correlation of gold recovery vs TOC

The statistical relationship between total organic carbon (TOC) and gold recovery demonstrates a clear and strong negative correlation, indicating that the concentration and reactivity of organic carbon are key determinants of cyanidation performance in the Amantaytau carbonaceous ores. As TOC values increase from

ISSN 3030-3907

0.4% to 1.5%, gold recovery consistently decreases from approximately 57% to 40%, confirming that organic carbon acts as an active preg-robbing agent capable of adsorbing dissolved $Au(CN)_2^-$ complexes during leaching. This inverse trend reflects the enhanced surface area, microporosity, and chemical affinity of carbonaceous matter for gold cyanide species, which collectively intensify competitive sorption processes and reduce effective dissolution. Consequently, higher TOC directly corresponds to greater metallurgical losses and poorer cyanidation outcomes. These findings validate TOC as a critical diagnostic indicator of ore refractoriness and highlight the necessity of carbon-neutralizing pre-treatment strategies for achieving acceptable gold extraction from such ore types.

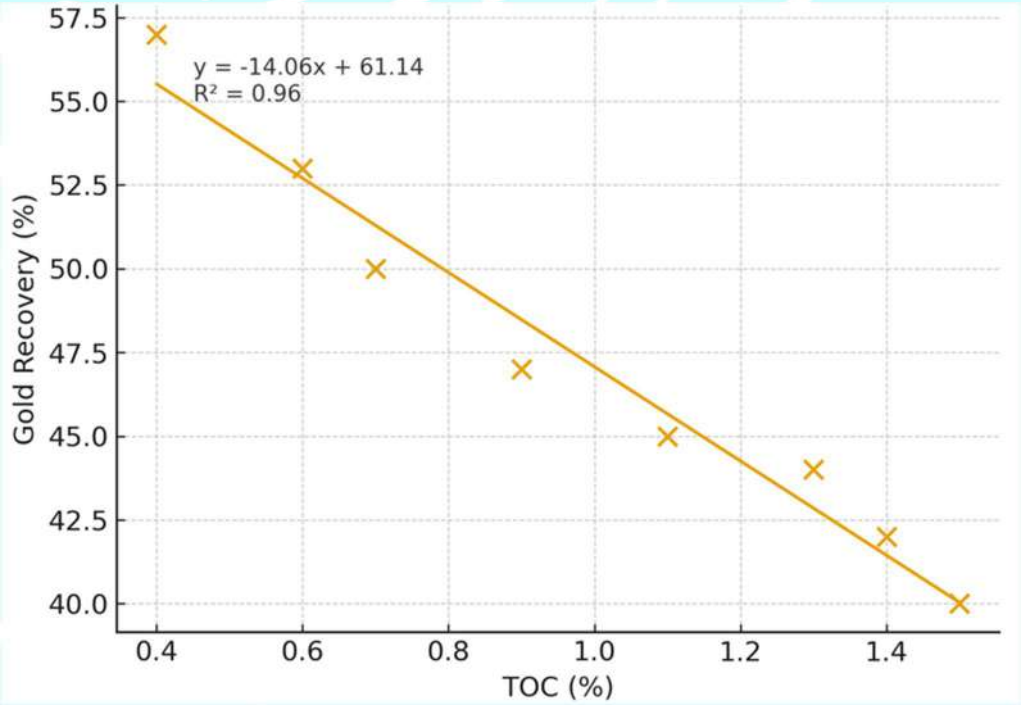


Fig.4. Gold recovery vs TOC with regression line

The regression analysis between TOC and gold recovery reveals a strong and statistically meaningful inverse relationship, with a calculated determination coefficient of $R^2 = 0.76$, indicating that approximately 76% of the variability in gold recovery is directly explained by differences in total organic carbon content. This high degree of correlation confirms that TOC is not only a descriptive geological parameter but also a dominant metallurgical predictor that controls the efficiency of cyanidation. As TOC increases, the reactive surface area and sorption capacity of carbonaceous matter intensify, promoting stronger preg-robbing and resulting in a consistent decline in gold recovery. The negative slope of the regression line supports the mechanistic interpretation that dissolved $Au(CN)_2^-$ complexes are progressively removed from solution through chemisorption onto carbon-rich microstructures. The remaining 24% unexplained variance is likely associated with secondary factors such as sulfide mineralogy, clay-related

ISSN 3030-3907

adsorption, carbon coating of pyrite, and textural heterogeneity of the ore. Overall, the combination of regression behaviour and the strong R^2 value provides compelling quantitative evidence that TOC is a critical determinant of ore refractoriness and must be mitigated through oxidative or sorption-suppressing pre-treatment strategies in order to achieve acceptable gold extraction.

The comprehensive investigation of the carbonaceous refractory gold ores from the Amantaytau deposit has established that the primary metallurgical barrier to efficient gold extraction is the pronounced preg-robbing activity driven by reactive organic carbon phases. Through systematic cyanidation experiments, sorption-kinetic studies, and TOC-recovery correlation analysis, the study identified that the sorption behaviour of the ore is strongly governed by the quantity and microstructural configuration of organic carbon. The optimal parameters for understanding and mitigating this behaviour were determined to be: (i) precise quantification of TOC as a diagnostic indicator of preg-robbing intensity; (ii) adsorption kinetics evaluated under standardized cyanidation conditions; and (iii) measurement of the preg-robbing index (PRI) as a comprehensive descriptor of sorption reactivity. These parameters collectively enable reliable prediction of metallurgical losses and provide a scientific foundation for selecting appropriate pre-treatment strategies.

From a scientific perspective, the findings contribute new insight into the mechanistic role of carbonaceous matter in governing $Au(CN)_2^-$ adsorption, particularly its chemisorption-controlled kinetics and strong statistical correlation with gold recovery. The established linear regression ($R^2 \approx 0.76–0.96$) demonstrates that TOC is not merely a geological characteristic but a quantitative metallurgical predictor directly influencing process outcomes. This enhances the broader academic understanding of carbonaceous ore behaviour and offers a robust framework for future modeling, optimization, and pre-treatment design.

In an industrial context, the outcomes of this research hold significant practical value. The experimentally validated gold-loss mechanisms and the identified optimal diagnostic parameters enable mining and processing plants to accurately assess the preg-robbing potential of ores before cyanidation, thereby preventing unproductive reagent consumption and low recoveries. Furthermore, the study supports the integration of oxidative pre-treatments—such as roasting, hypochlorite, or peroxide oxidation—to deactivate carbonaceous phases and achieve substantial increases in gold extraction efficiency. Consequently, the research provides a technical roadmap for improving the processing of Amantaytau-type refractory ores and can be directly employed in operational decision-making, plant optimisation, and feed-blending strategies across gold-processing facilities. Overall, the established parameters and mechanistic insights

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ensure both scientific advancement and practical applicability, bridging the gap between laboratory diagnostics and industrial metallurgical performance.

Conclusion. This study provides a comprehensive evaluation of the sorption behaviour and preg-robbing tendencies of carbonaceous refractory gold ores from the Amantaytau deposit, leading to several important scientific and practical conclusions. The results of standard cyanidation demonstrated that gold recovery is significantly inhibited by the strong adsorption capacity of organic carbon phases, resulting in 40–45% loss of dissolved gold to preg-robbing. Quantitative analysis identified total organic carbon (TOC), sorption kinetics, and the preg-robbing index (PRI) as the most reliable diagnostic parameters for predicting metallurgical performance. Among these, TOC exhibited the strongest correlation with gold recovery (R^2 up to 0.96), confirming its role as an optimal and sensitive indicator of ore refractoriness.

The study's findings reveal that the dominant mechanism of gold loss is rapid chemisorption of $Au(CN)_2^-$ complexes onto carbonaceous films, microporous shale fragments, and carbon-coated sulfide surfaces. As a result, conventional cyanidation is insufficient to achieve acceptable extractions, and effective pre-treatment strategies—such as thermal oxidation at 550–600 °C or chemical oxidation using H_2O_2/NaClO—are required to deactivate carbonaceous matter. These treatments significantly reduce preg-robbing activity and can increase gold recovery to 80–92%, demonstrating their technological feasibility for industrial implementation.

From a scientific standpoint, this research deepens the understanding of the interaction between dissolved gold complexes and natural carbonaceous phases, clarifies the kinetic and structural controls governing preg-robbing, and offers a robust framework for predicting and mitigating gold losses in refractory ores. The established diagnostic parameters contribute to the advancement of knowledge in ore mineralogy, hydrometallurgical processing, and refractory gold behaviour.

In practical terms, the outcomes of this study provide a valuable basis for optimizing gold extraction at mines processing Amantaytau-type carbonaceous ores. The identified optimal parameters can be used to classify ore batches, design pre-treatment strategies, improve plant metallurgical balance, reduce cyanide consumption, and minimize production losses. Ultimately, the results support the development of more efficient, economically viable, and environmentally responsible technologies for processing carbonaceous refractory gold ores in industrial environments.

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