

Article

Geometallurgical Diagnosis of Gold Loss in Refractory Quartz-Vein Gold Tailings Using Automated Mineralogy: A Case Study of the Baolun Gold Mine, Hainan Province, China

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Abstract

To enhance gold recovery from tailings of a quartz-vein gold deposit in Hainan, China, this study systematically characterized the chemical composition, mineral composition, and process mineralogical characteristics of gold particles using inductively coupled plasma optical emission spectrometry (ICP-OES), Advanced Mineral Identification and Characterization System (AMICS), and scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS). The results show that the tailings have an average gold grade of 0.44 g/t, and the gold occurs predominantly as native gold (average fineness approximately 92%). The gold grains are predominantly fine ($89.74\% < 10\ \mu\text{m}$, $n = 312$), with 92.31% occurring as locked inclusions, predominantly in quartz and chlorite. Particle-size-dependent liberation analysis reveals that gold liberation is strongly size-dependent: 42.31% of the total gold resides in the $-5\ \mu\text{m}$ fraction, where grains are almost entirely locked and complete mechanical liberation is technically and economically unattainable. The fine-grain size and insufficient liberation of gold from gangue minerals are the primary causes of gold loss during processing. Additionally, chlorite, as the dominant locking mineral, is prone to overgrinding and likely induces slime coating on gold surfaces, further impairing flotation recovery. A two-pronged optimization strategy is hypothesized: regrinding to a P80 of 20–45 μm combined with dispersants such as sodium silicate or sodium hexametaphosphate. These findings provide a scientific basis for gold recovery from these tailings and for the processing of similar refractory gold tailings.

Keywords: automated mineralogy; refractory gold tailings; slime coating; particle-size-dependent liberation; mineral liberation; geometallurgy

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1. Introduction

Gold is a strategically important resource widely used in modern technology, finance, and industry. Rising global gold demand has driven increased ore mining and processing, generating large volumes of tailings that pose significant environmental and safety challenges [1–8]. At the same time, these tailings represent a potential secondary resource, often containing valuable metals incompletely recovered by the original processing circuits [9–12]. Recovering residual gold from tailings aligns with circular economy principles and improves the sustainability of mining operations [13–15].

In refractory gold ores, gold is often finely disseminated and tightly locked within gangue minerals, posing special challenges for recovery [16–19]. Previous studies have shown that a significant proportion of gold loss to tailings can be attributed to mineralogical factors, notably the failure to adequately liberate micron-sized gold particles during comminution [20–22]. In particular, phyllosilicate gangue minerals such as chlorite are known to adversely affect flotation recovery through overgrinding and slime coating [23–25]. Therefore, gold recovery efficiency is intrinsically linked to its mode of occurrence—the grain size, morphology, mineral associations, and degree of liberation of gold particles [22,26–28].

Quartz-vein-hosted gold deposits are among the most important global sources of gold and the dominant industrial type of gold deposits in China [29–33]. Although the geology of these deposits has been extensively studied, detailed process mineralogical investigations specifically quantifying the locking characteristics of residual gold in their tailings remain scarce [34]. Previous geometallurgical studies on quartz-vein gold tailings have rarely combined quantitative automated mineralogy with detailed analysis of gold locking mechanisms, and particle-size-dependent liberation data are particularly lacking.

This study addresses this gap through a systematic geometallurgical diagnosis of gold loss in tailings from the Baolun gold mine, the largest high-grade quartz-vein gold deposit on Hainan Island, South China. Specifically, this study (i) provides the first particle-size-dependent liberation dataset for quartz-vein gold tailings; (ii) presents a multi-line evidence framework for chlorite slime coating based on EDS, trace element geochemistry, and high-resolution BSE imaging; and (iii) proposes an evidence-based two-pronged strategy for process optimization. The results offer a scientific basis for gold reprocessing from such tailings and provide a valuable reference for the characterization and sustainable recovery of analogous refractory quartz-vein gold resources.

2. Geological Setting of the Baolun Gold Deposit

The Baolun gold deposit is located in Ledong County, southwestern Hainan Island, South China. Tectonically, it lies within the Wuzhishan fold belt of the South China fold system [35]. The Indosinian Jianfengling biotite granite pluton occurs to the northwest of the deposit. It is the largest gold deposit on Hainan Island, with proven reserves exceeding 80 t at an average grade of approximately 10.3 g/t [36,37].

The ore-hosting strata belong to the Lower Silurian Tuolie Formation, consisting predominantly of carbonaceous sericite phyllite and sericite siltstone. The orebodies are mainly hosted in the sericite-quartz phyllite of the lower member of the Tuolie Formation [35,38].

The dominant intrusive body in the district is the Indosinian Jianfengling coarse-grained porphyritic biotite syenogranite, emplaced during the Middle Triassic (249–236 Ma) [39]. Diabase dikes are spatially associated with the auriferous quartz veins, with an emplacement age (231.6 ± 2.6 Ma) that coincides with the mineralization age within analytical error [40].

The orebodies are controlled by a series of NNW-trending brittle–ductile fracture zones. The Haogangling anticline, combined with these fractures, provided favorable dilatational sites for fluid flow and gold precipitation [35,38].

Hydrothermal alteration is pervasive and includes silicification, sericitization, chloritization, carbonatization, and sulfidization [38,41].

The orebodies occur as veins and lenses. The dominant ore type is quartz-vein type, with subordinate altered-rock type. The ore mineral assemblage comprises native gold, pyrite, pyrrhotite, arsenopyrite, and minor bismuthinite. Gangue minerals are mainly quartz, muscovite, sericite, chlorite, and calcite [38,41,42].

Based on mineral paragenesis and crosscutting relationships, four mineralization stages are recognized [42] (Figure 1):

Mineral	Stage I	Stage II	Stage III	Stage IV
Coarse Quartz	■			
Fine Quartz		■	■	■
Muscovite/Sericite	■	■		
Pyrite		■		
Pyrrhotite		■		
Arsenopyrite		■		
Native Gold		■ ■ ■ ■	■ ■	
Chlorite	■	■		
Bismuthinite			■ ■ ■ ■	
Native Bismuth			■ ■	
Calcite				■ ■ ■ ■ ■ ■ ■ ■ ■ ■

Figure 1. Ore and alteration minerals of each mineralization stage in the Baolun gold deposit.

Stage I (Gold–coarse quartz stage): Characterized by coarse-grained milky quartz with homogenization temperatures of 248–376 °C. This stage is essentially barren.

Stage II (Gold–fine quartz stage, main mineralization): Characterized by fine-grained quartz and abundant sulfides (pyrite, pyrrhotite, arsenopyrite), with temperatures of 213–320 °C [42]. Native gold occurs as micro-fine grains (<10 µm) enclosed within quartz and sulfides.

Stage III (Gold–bismuthide–sulfide–quartz stage): Native gold co-precipitated with bismuth minerals (bismuthinite, native bismuth) at temperatures of 150–200 °C.

Stage IV (Carbonate stage): Characterized by calcite and minor quartz veins, representing the waning phase of hydrothermal activity.

Multiple isotopic dating methods constrain the mineralization age to 228–219 Ma (Late Triassic), consistent with the late-stage emplacement age of the Jianfengling granite and the diabase dikes, indicating a magmatic–hydrothermal origin [36,38,43].

3. Materials and Methods

3.1. Test Materials

The concentrator at the Baolun gold mine has a design capacity of 450 t/d. The grinding product of the concentrator has a P80 (80% passing size) of approximately 75 µm. The original flotation conditions were as follows: butyl xanthate and ammonium butyl dithiophosphate as collectors, 2# oil as frother, pH 9.0–9.5, SF mechanical flotation cells, and total residence time of 15 min. Tailings samples were collected from three representative areas of the tailings storage facility. In each area, one sample was taken every 50 m, yielding a total of nine samples. After being transported to the laboratory, the samples were naturally dried, thoroughly mixed, and then split for subsequent analysis and testing.

3.2. Analytical Methods

3.2.1. Chemical Composition Analysis

Tailings samples were submitted to Zhongye Yiju (Hebei) Testing Technology Co., Ltd. (Yanjiao, China) for multi-element whole-rock chemical analysis. Major and minor elements were determined by inductively coupled plasma optical emission spectrometry (ICP-OES, Thermo Fisher Scientific, Waltham, MA, USA) following the method described in ISBN 978-7-116-07130-8 (in Chinese) issued by the China Geological Survey (CGS). Trace elements were analyzed by inductively coupled plasma mass spectrometry (ICP-MS, Thermo Fisher Scientific, Waltham, MA, USA, detection limit 0.001 mg/kg) according to the standard ISBN 978-7-116-07129-2. Before analysis, samples were digested using a four-acid open dissolution method ($\text{HNO}_3\text{-HCl-HClO}_4\text{-HF}$) at 180–220 °C for 3–4 h. Gold content was determined by foam plastic adsorption enrichment coupled with graphite furnace atomic absorption spectrometry (PF-GFAAS, Hitachi High-Tech Corporation, Tokyo, Japan, detection limit 0.1 ng/g). High-purity water prepared with a Milli-Q ultrapure water system was used throughout the analysis. Quality assurance and quality control (QA/QC) procedures included replicate analyses, blank samples, and standard reference materials for ICP-MS analysis.

3.2.2. Mineral Liberation Analysis (AMICS)

The mineral composition, particle size distribution, liberation degree, and textural features of the tailings were determined using the Advanced Mineral Identification and Characterization System (AMICS) at the Institute of Mineral Resources, Chinese Academy of Geological Sciences. First, the tailings samples were mixed with graphite powder and epoxy resin to prepare 30 resin mounts (30 mm diameter), which were then polished to expose tens of thousands of individual particles on the surface. After carbon coating, the mounts were measured using the AMICS. AMICS is the third-generation automated mineral parameter quantification system developed by Gu Ying's team following QEMSCAN and MLA [44–46]. The system consists of a ZEISS Sigma300 field-emission scanning electron microscope (ZEISS, Oberkochen, Germany) equipped with two Bruker XFlash6/60 X-ray energy-dispersive spectrometers (Bruker Corporation, Berlin, Germany) and the AMICS software (v3.3.4) package [47]. Measurements were performed in particle mode with an accelerating voltage of 20 kV, a working distance of 10.0 mm, a backscattered electron (BSE) detector, image brightness calibrated using a pure gold standard, and an objective aperture of 120 μm . A total of 1282,773 individual particles were analyzed across 30 resin mounts. From these, 312 gold particles were identified and subjected to detailed morphological classification, EDS analysis, and liberation characterization.

3.2.3. Scanning Electron Microscopy (SEM)

After AMICS analysis, the samples were further examined using a scanning electron microscope (SEM). High-magnification imaging and energy-dispersive spectroscopy (EDS) of the identified gold grains were performed using a JEOL IT500 scanning electron microscope (JEOL Ltd., Tokyo, Japan), operated in BSE mode with an operating current of 10 nA and an accelerating voltage of 20 kV. The built-in EDS was used to obtain compositional data of the tailings particles. The EDS analysis was standardless, using the instrument's built-in ZAF correction method for semi-quantitative analysis, and all measured components were normalized to 100%.

4. Results

4.1. Chemical Composition

Multi-element chemical analysis results of the gold tailings are shown in Table 1. The tailings have an arithmetic mean gold grade of 0.44 g/t (standard deviation = 0.21 g/t), with individual samples reaching up to 0.787 g/t and as low as 0.17 g/t. Other metal elements include Ag, Cu, Pb, Zn, and Fe, but their contents are generally low and not individually economically recoverable under current market conditions. The SiO₂ content in the tailings is 71.87%, with Al₂O₃ at 12.74%, TFe₂O₃ at 5.44%, and K₂O at 3.40%. The grade variability observed among samples is attributed to the inherent heterogeneity of gold distribution within the tailings storage facility. This variability suggests that selective mining of higher-grade zones within the tailings may enhance the economic viability of future reprocessing efforts.

Table 1. Multi-element chemical analysis results of the gold tailings ($n = 9$).

	Element	Sample Number	Mean	Standard Deviation	Maximum	Minimum
%	FeO	9	4.57	0.49	5.31	4.03
%	SiO ₂	9	71.87	1.84	73.77	69.06
%	Al ₂ O ₃	9	12.74	0.53	13.79	12.02
%	CaO	9	1.62	0.33	2.03	1.13
%	TFe ₂ O ₃	9	5.44	0.47	6.10	4.94
%	K ₂ O	9	3.40	0.19	3.79	3.23
%	MgO	9	1.88	0.24	2.18	1.56
%	Na ₂ O	9	0.40	0.03	0.42	0.33
%	MnO	9	0.08	0.00	0.09	0.08
%	P ₂ O ₅	9	0.05	0.00	0.06	0.04
%	TiO ₂	9	0.47	0.02	0.51	0.44
mg/kg	As	9	59.14	27.47	109.54	30.35
μg/kg	Hg	9	5.98	1.46	7.70	3.93
mg/kg	Pb	9	14.57	2.58	19.07	12.15
mg/kg	Cs	9	12.34	1.27	13.97	10.90
mg/kg	Cu	9	10.66	1.39	12.50	8.74
mg/kg	Zn	9	54.76	7.23	66.55	46.40
mg/kg	Cr	9	101.22	7.01	114.23	90.37
mg/kg	Co	9	8.99	2.00	12.78	7.12
mg/kg	Ni	9	17.94	2.85	22.95	14.81
mg/kg	Cd	9	0.07	0.03	0.11	0.03
mg/kg	Sb	9	0.74	0.21	1.05	0.49
mg/kg	Ba	9	374.75	20.45	414.66	349.60
mg/kg	Ag	9	0.09	0.05	0.16	0.04
g/t	Au	9	0.44	0.21	0.79	0.17

Note: TFe₂O₃ represents total iron calculated as Fe₂O₃.

4.2. Mineral Composition

Table 2 presents the mineral composition of the gold tailings as determined by AMICS analysis. The total metallic mineral content is 1.94%, including pyrrhotite, ilmenite, and trace amounts of rutile and magnetite. The gangue mineral content accounts for the remaining 98.05%, predominantly consisting of quartz, muscovite, chlorite, and feldspar. Quartz and muscovite are the two most abundant minerals, accounting for 52.77% and 28.62%, respectively.

Table 2. Mineral composition of the gold tailings.

Mineral	Content (%)	Mineral	Content (%)
Quartz	52.77	Pyrrhotite	1.46
Muscovite	28.62	Ilmenite	0.37
Chlorite	7.59	Rutile	0.09
Biotite	2.28	Magnetite	0.02
Feldspar	3.37		
Calcite	0.91		
Others	2.51		
Gangue minerals total	98.05	Metallic minerals total	1.94

4.3. Process Mineralogical Characteristics of Gold Minerals

4.3.1. Composition of Gold Minerals

Native gold is the predominant gold mineral. Representative EDS analyses were performed on selected gold grains exhibiting different locking relationships and host mineral associations. The average compositions of these analyses are summarized in Table 3. The mean gold content ranges from 89.66% to 93.26% among the analyzed samples, with an overall average fineness of approximately 92%. Most gold grains contain 2%–7% silver. Elevated oxygen contents (up to 5.75 wt% mean) were observed in all analyzed samples (Table 3).

Table 3. EDS compositions of selected gold grains (wt%).

Sample ID	Points (n)	Au	Ag	Fe	O	Host Mineral Association
BLT3-1-01	5	90.32	6.36	0.79	2.53	Quartz-hosted
BLT3-2-01	5	93.26	4.79	—	0.26	Chlorite-associated
BLT3-2-02	4	91.67	5.88	—	0.53	Chlorite-associated
BLT15-1-02	4	89.66	—	0.35	5.75	Chlorite-associated
Overall Mean		~92				

Note: Results are semi-quantitative, normalized to 100 wt%. The analyses represent a subset of gold grains selected to cover the range of observed locking relationships (quartz-hosted, chlorite-associated). — = below detection limit.

4.3.2. Grain Size of Gold Minerals

The grain size distribution of 312 gold grains, based on particle counts, is shown in Table 4. As shown in Table 4, 89.74% of the gold grains are finer than 10 μm (cumulative undersize). Among these, the largest proportion (47.44%) falls in the 5–10 μm range, and 34.62% in the 2–5 μm range. Grains finer than 2 μm account for 7.69%. The coarser fraction (10–37 μm) accounts for only 10.26%, and these grains are without exception all locked in quartz or chlorite. The largest gold grain observed measures 19.4 $\times$ 6.3 μm . It is tabular, has a rough surface (Figure 2), and is locked in chlorite.

The grain size distribution data reveal a pronounced fine-skewed character. A dominant 82.06% of gold grains fall within the 2–10 μm size range (the sum of $-10 + 5$ and $-5 + 2$ fractions), with a median size (d_{50}) estimated at approximately 6 μm . The population is bimodal with a primary mode in the 5–10 μm range and a secondary mode in the 2–5 μm range. This distribution has direct implications for the target grind size required for liberation.

An approximate mass distribution was estimated to complement the number-based grain size data. Assuming spherical gold grains and using the mean diameter of each size fraction cubed (d^3) as a proxy for grain volume, the mass contribution of each fraction was

estimated. The $-10 + 5 \mu\text{m}$ fraction, with a measured mean diameter of $5.73 \mu\text{m}$, contributes approximately 55.6% of the total gold mass, consistent with its dominant numerical proportion (47.44%). The $-5 + 2 \mu\text{m}$ fraction (mean diameter $2.76 \mu\text{m}$) accounts for approximately 24.3% of the gold mass. The coarsest fraction ($-37 + 10 \mu\text{m}$, mean diameter $12.20 \mu\text{m}$) contributes approximately 19.4% of the gold mass, substantially more than its 10.26% numerical proportion but less than the dominant $-10 + 5 \mu\text{m}$ fraction. The finest fraction ($-2 \mu\text{m}$, mean diameter $1.50 \mu\text{m}$) contributes less than 1% of the gold mass despite representing 7.69% of grains by number. These estimates confirm that the $2\text{--}10 \mu\text{m}$ range ($-10 + 5 \mu\text{m}$ and $-5 + 2 \mu\text{m}$ fractions combined), which accounts for 82.06% of gold grains by number, also contributes approximately 80% of the gold mass, indicating that the number-based distribution is a reasonable proxy for the mass distribution in these tailings.

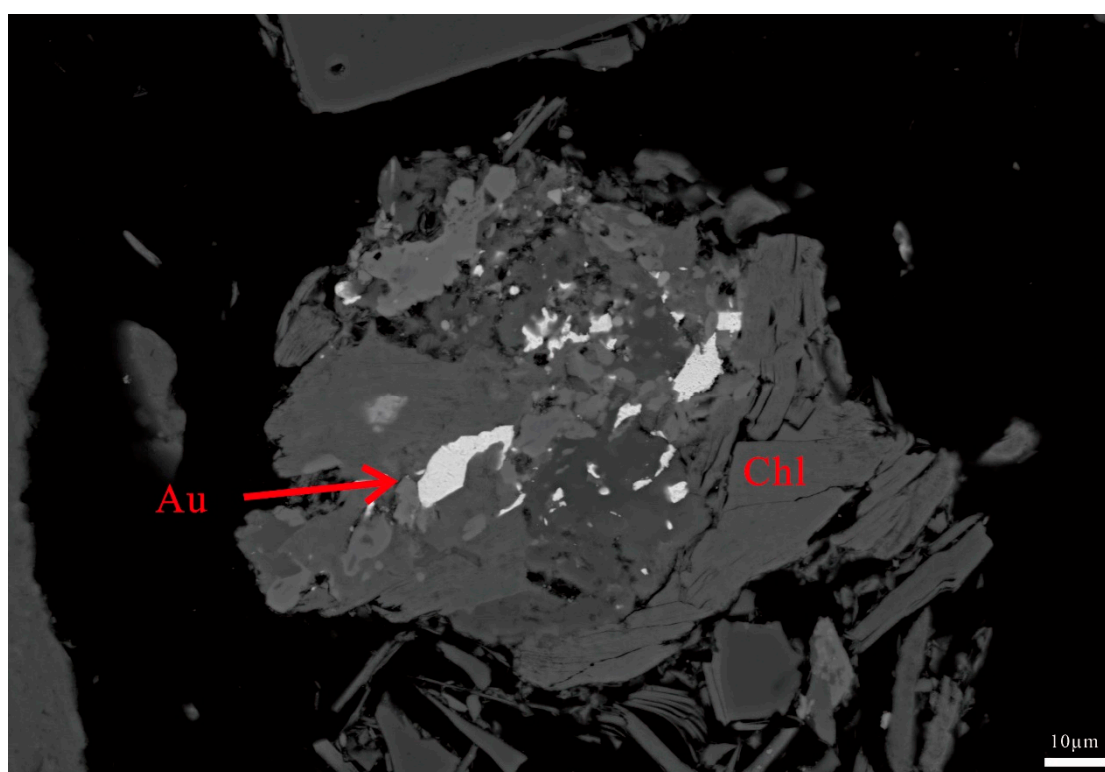


Figure 2. BSE image of the largest gold grain ($19.4 \times 6.3 \mu\text{m}$). The grain is tabular and locked in chlorite.

Table 4. Grain size distribution of gold particles ($n = 312$).

Grain Size (μm)	$-37 \text{ to } +10$	-10			Total
		$-10 \text{ to } +5$	$-5 \text{ to } +2$	-2	
Number percentage (%)	10.26	47.44	34.62	7.69	100

Note: The notation $-X + Y$ denotes particles passing a sieve of aperture $X \mu\text{m}$ but retained on a sieve of aperture $Y \mu\text{m}$.

4.3.3. Morphology of Gold Minerals

A total of 312 gold grains were classified by their two-dimensional projected morphology into seven types (Figure 3): elongated angular, wheat-like, sharp angular, tabular, dendritic, rounded, and irregular. The statistics are summarized in Table 5.

As shown in Figure 4 and Table 5, elongated angular and wheat-like grains are the dominant morphological types, together accounting for 78.21% of the total gold grain population, while each of the other types accounts for less than 10%. Elongated angular gold grains are the most abundant (47.44%), with an average size of $7.26 \mu\text{m}$. Wheat-like gold

grains account for 30.77% of the population but have the smallest average size (2.63 μm). Sharp angular and tabular grains have relatively larger average sizes (8.5 μm and 5.86 μm , respectively). Dendritic grains account for the smallest proportion (2.56%) but have the largest average size (10.5 μm). Rounded and irregular grains together represent less than 4% of the total.

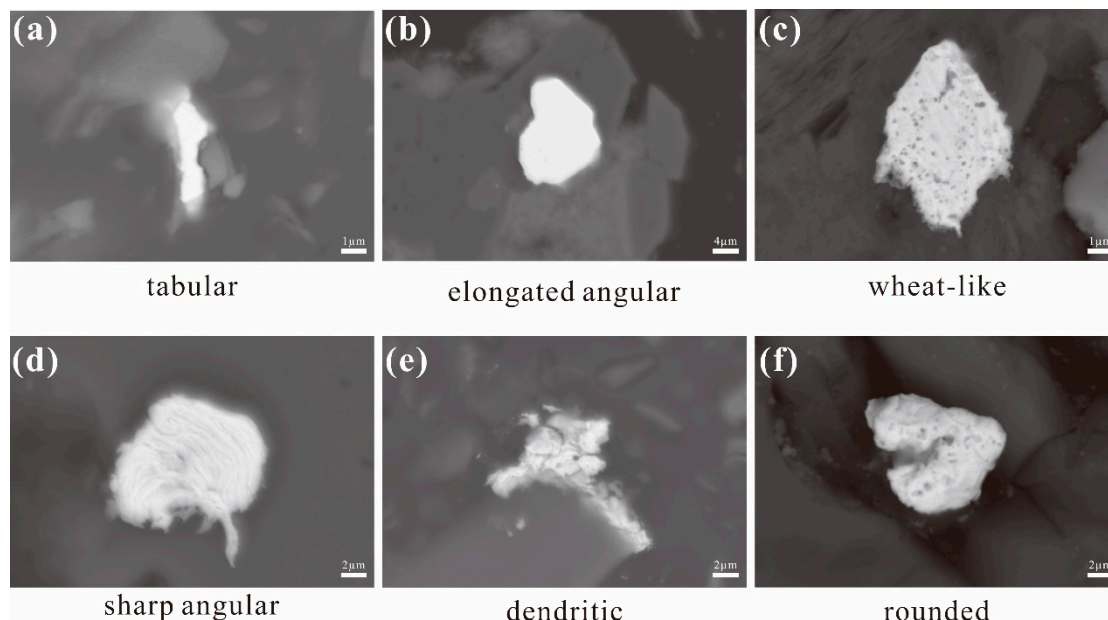


Figure 3. Images showing various morphologies of gold grains.

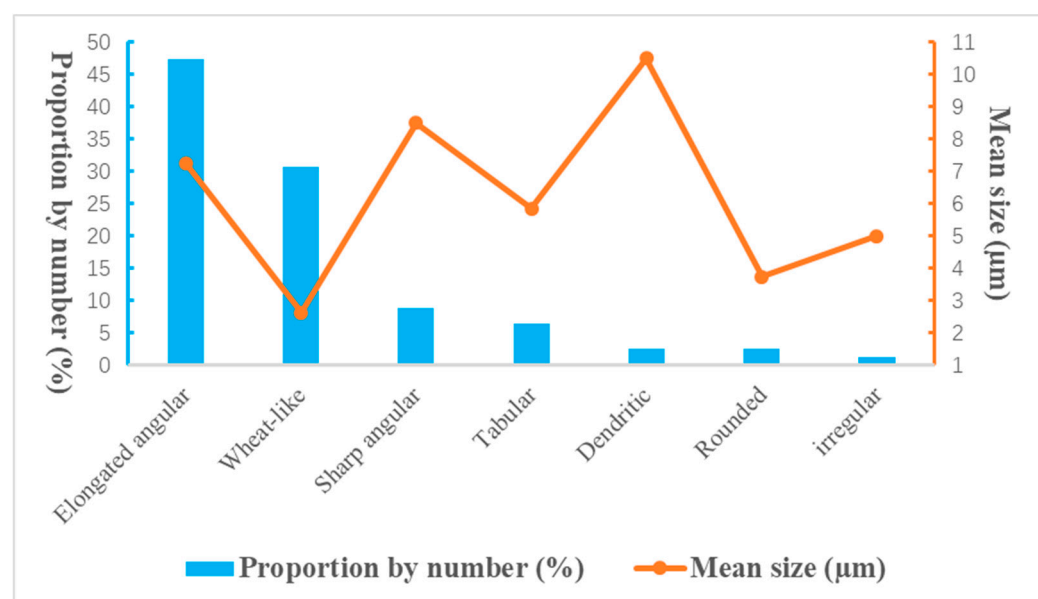


Figure 4. Morphology distribution of gold grains ($n = 312$). The dominant elongated, angular, and wheat-like types together account for 78.21% of the total gold grain population.

Table 5. Morphology statistics of gold grains ($n = 312$).

Gold Particle Morphology	Proportion by Number (%)	Mean Size (μm)
Elongated angular	47.44	7.26
Wheat-like	30.77	2.63
Sharp angular	8.97	8.5
Tabular	6.41	5.86
Dendritic	2.56	10.5

Rounded	2.56	3.75
Irregular	1.28	5

Note: The wheat-like category includes grains with the smallest mean size ($2.63\ \mu\text{m}$) and accounts for nearly one-third of the total gold grain population.

4.3.4. Textural Characteristics of Gold Minerals

SEM-BSE images were used to characterize the occurrence features of gold grains relative to gangue minerals (Figure 5). Gold grain liberation was classified following the area fraction thresholds of Mariano [48]: locked (gold area <30%), marginal (30%–60%), and liberated (>60%).

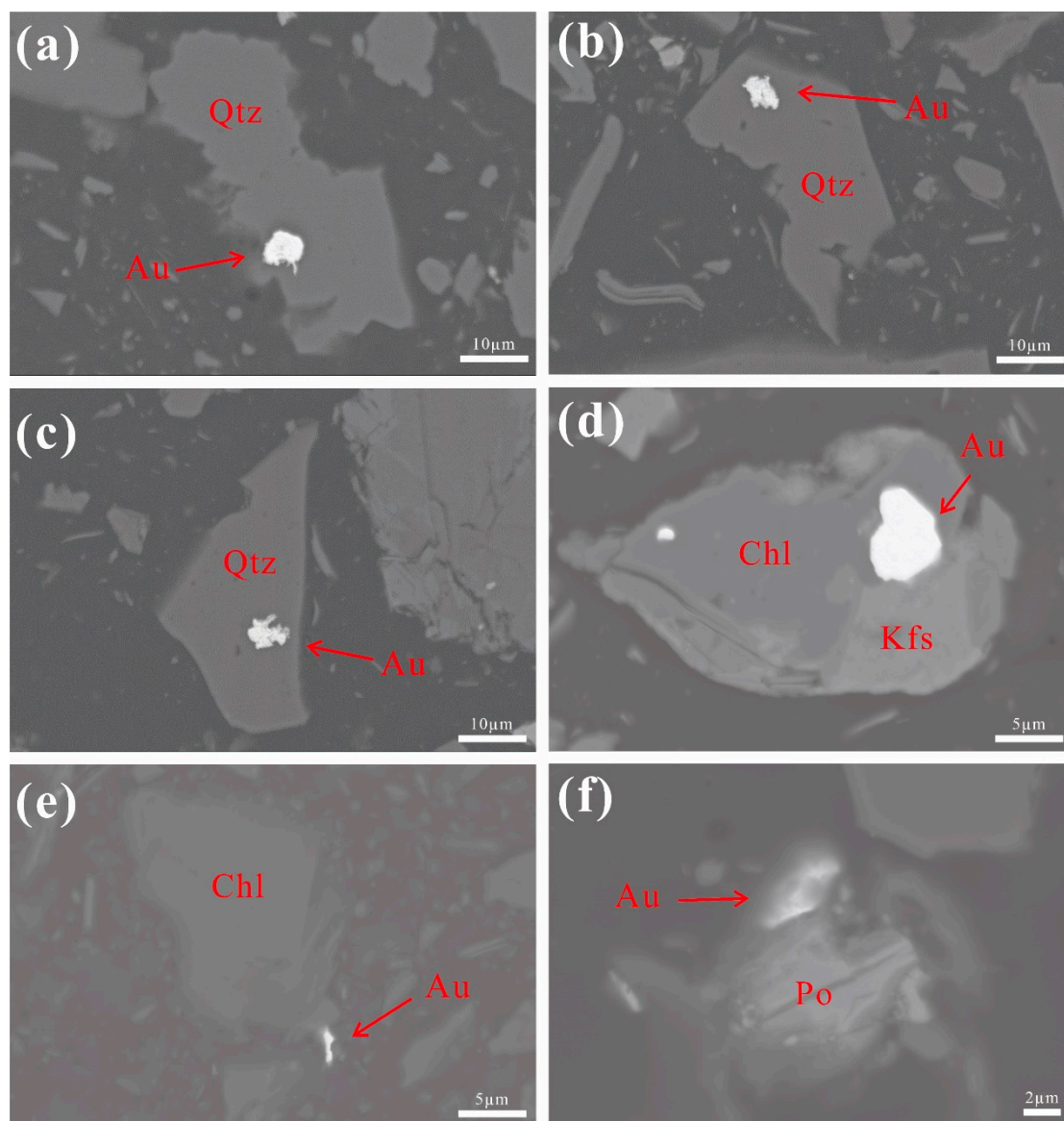


Figure 5. SEM-BSE images showing occurrences of gold grains in relation to gangue minerals. (a–c) gold grains hosted in quartz; (d) gold grain locked in Chl and Kfs; (e) tabular gold grain at the edge of Chl; (f) angular gold grain at the edge of pyrrhotite. Au = Native gold, Qtz = Quartz, Chl = Chlorite, Po = Pyrrhotite, and Kfs = K-feldspar.

The proportions of gold associated with different gangue minerals are presented in Figure 6. Chlorite is the most abundant association (49.35%), followed by quartz (40.26%) and pyrrhotite (5.19%). Muscovite and K-feldspar together account for the remaining

5.20%. Of the 308 locked and marginal gold grains, 15.6% were binary particles (gold associated with two gangue minerals, predominantly chlorite and K-feldspar), while the remaining 84.4% were associated with a single gangue mineral type.

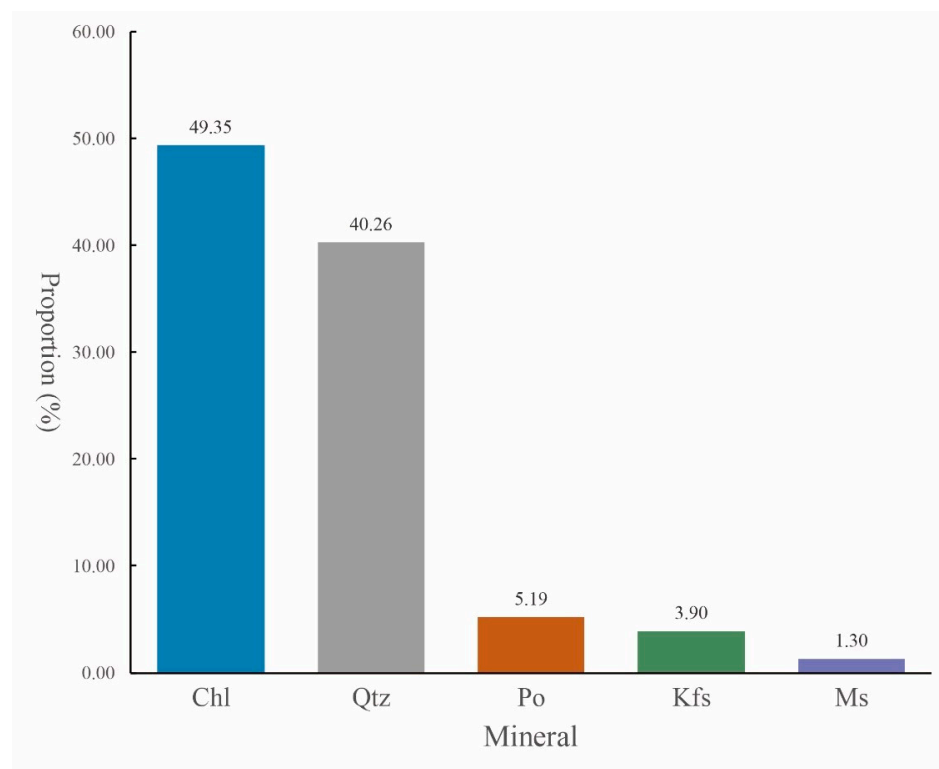


Figure 6. Statistics of gangue minerals associated with gold grains. Qtz = Quartz, Chl = Chlorite, Po = Pyrrhotite, Ms = Muscovite, and Kfs = K-feldspar.

Among the 312 counted gold grains, the overall locking state of gold grains is overwhelmingly dominated by locked gold, which accounts for 92.31% (Figure 7). All locked gold grains are micro-fine, with an average size of 5.01 μm . Marginal gold, occurring along the edges of gangue particles, accounts for 6.41%. This type is mainly tabular, with an average size of 5.66 μm . Completely liberated gold grains account for only 1.28% (Figure 8).

However, the overall liberation statistics mask a strong particle-size dependence, as revealed in Table 6. In the $-37 + 10 \mu\text{m}$ fraction, which accounts for 10.26% of total gold grains, 100.00% are completely locked, predominantly within quartz. No liberated or marginal gold is observed in this size range. In the dominant $-10 + 5 \mu\text{m}$ fraction, representing nearly half (47.44%) of the total gold grain population, 91.89% of grains remain fully locked, with chlorite as the dominant locking mineral. Only 8.11% occur as marginal gold along the edges of quartz and pyrrhotite grains. No completely liberated gold grains are found in this size fraction. In the $-5 + 2 \mu\text{m}$ fraction (34.62% of total), 88.89% of grains are locked, 7.41% are marginal, and 3.70% are fully liberated—the liberated gold found among all size fractions. The locking minerals in this fraction are predominantly quartz and chlorite. In the finest $-2 \mu\text{m}$ fraction (7.69% of total), all gold grains are completely locked, predominantly in quartz, with no liberated or marginal gold observed.

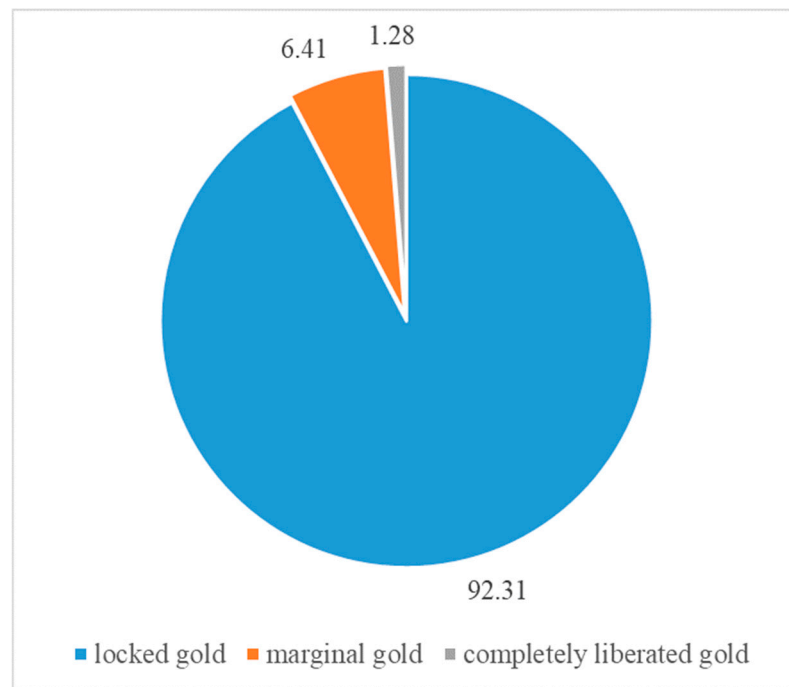


Figure 7. Distribution of gold grain occurrence states. Locked gold dominates (92.31%), with marginal and liberated gold representing only 6.41% and 1.28%, respectively.

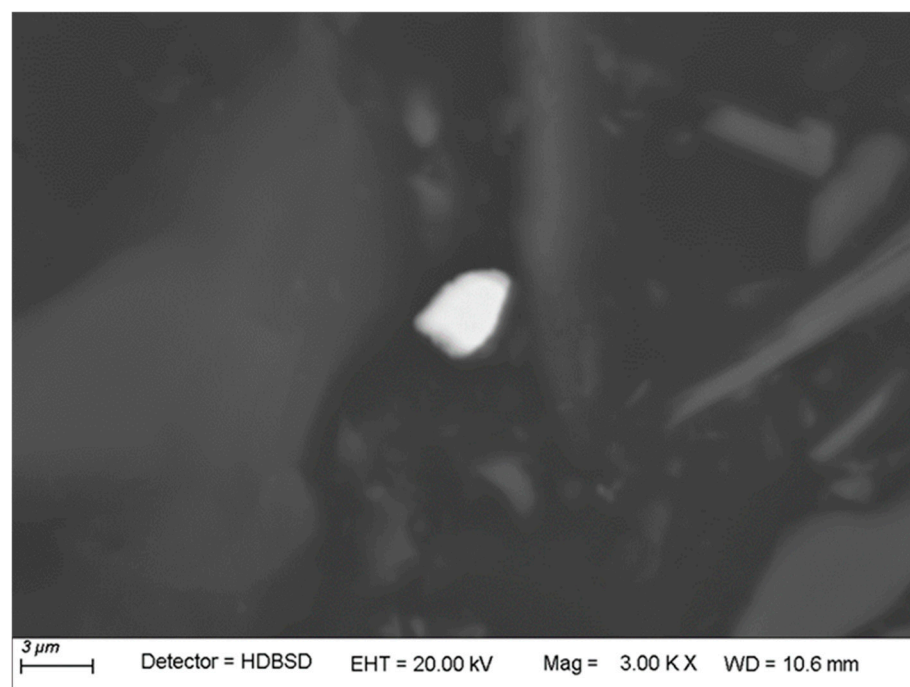


Figure 8. A completely liberated gold grain.

Table 6. Gold liberation characteristics by particle size class ($n = 312$ gold grains).

Particle Size Class (μm)	Percentage of Total (%)	Liberated (%)	Marginal (%)	Locked (%)	Dominant Locking Mineral (s)
−37 + 10	10.26	0	0	100	Quartz
−10 + 5	47.44	0	8.11	91.89	Chlorite
−5 + 2	34.62	3.7	7.41	88.89	Quartz, Chlorite
−2	7.69	0	0	100	Quartz, Chlorite
Total	100	—	—	—	—

Table 7 provides a quantitative breakdown of the locking mineralogy by particle size fraction. A clear size-dependent shift in the dominant locking mineral is observed. In the $-37 + 10\ \mu\text{m}$ and $-5 + 2\ \mu\text{m}$ fractions, quartz is the primary locking mineral, hosting 75.0% of locked gold grains in each. In the $-2\ \mu\text{m}$ fraction, quartz also dominates (66.7%). In contrast, in the $-10 + 5\ \mu\text{m}$ fraction—which alone accounts for 47.44% of total gold grains—chlorite is overwhelmingly dominant, hosting 88.2% of all locked gold.

Table 7. Locking mineral distribution by particle size class (% of locked gold in each fraction).

Particle Size Class (μm)	Quartz (%)	Chlorite (%)	Pyrrhotite (%)	K-Feldspar (%)
$-37 + 10$	75.0	25.0	—	—
$-10 + 5$	5.9	88.2	—	5.9
$-5 + 2$	75.0	16.7	4.2	4.2
-2	66.7	33.3	—	—

Note: Percentages are calculated as the proportion of locked gold grains in each size fraction hosted by each gangue mineral. — = not detected in that fraction. Muscovite was not detected as a locking mineral in any size fraction.

Taken together, these data reveal two critical features of the gold occurrence. First, a dominant 82.06% of gold grains are concentrated in the $2\text{--}10\ \mu\text{m}$ size range ($-10 + 5$ and $-5 + 2$ fractions combined), where complete liberation is rarely achieved. Second, chlorite is the predominant locking mineral in the largest single size fraction ($-10 + 5\ \mu\text{m}$, accounting for nearly half of all gold grains), hosting 88.2% of locked gold in this fraction (Table 7), indicating a particularly intimate gold–chlorite association that has direct consequences for any regrinding strategy.

5. Discussion

5.1. Dominant Causes of Gold Loss

5.1.1. The Liberation–Grind Size Gap

Automated mineralogy provides a systematic, quantitative diagnosis of gold loss in the Hainan quartz-vein gold tailings. The results reveal a classic case of mineralogical re-fractoriness, where the fine grain size and locking state of the residual gold render it unrecoverable by the current processing circuit.

The primary cause of gold loss is the substantial gap between the gold grain size and the current grinding product size. As shown in Table 4 and Figure 7, 89.74% of the gold grains are finer than $10\ \mu\text{m}$, of which 92.31% occur as locked particles. The current grinding circuit at the mine operates with a product size P80 of approximately $75\ \mu\text{m}$, nearly an order of magnitude coarser than the dominant gold grain size population. From first principles of mineral liberation, particles must be ground to a size approaching that of the target mineral grains to achieve substantial liberation [49,50]. The current $75\ \mu\text{m}$ grind is therefore fundamentally inadequate for liberating gold grains that are predominantly in the $2\text{--}10\ \mu\text{m}$ range. It should be noted that gold grains finer than approximately $1\text{--}2\ \mu\text{m}$ are below the effective detection limit of AMICS and may be underrepresented in the reported grain population. Consequently, the liberation statistics—particularly for the $-2\ \mu\text{m}$ fraction—should be regarded as estimates based on the detectable grain population.

5.1.2. Particle-Size-Dependent Liberation and Its Implications for Regrinding

The particle-size-dependent liberation data (Table 6) provide critical insight into what a finer grind can and cannot achieve. In the $-37 + 10\ \mu\text{m}$ fraction (10.26% of total

gold), 100.00% of grains remain fully locked within quartz, indicating that even the coarsest gold particles require substantial size reduction before any exposure is achieved. More importantly, in the $-10 + 5 \mu\text{m}$ and $-5 + 2 \mu\text{m}$ fractions, which together account for 82.06% of total gold grains, locked gold accounts for 91.89% and 88.89%, respectively, with chlorite as the dominant locking mineral. Even in the $-5 + 2 \mu\text{m}$ fraction, only 3.70% of gold grains are fully liberated.

Based on these liberation characteristics, we hypothesize that a regrind P80 in the range of 20–45 μm would be required to shift a meaningful portion of the gold in the $-37 + 10 \mu\text{m}$ and $-10 + 5 \mu\text{m}$ fractions toward a marginal or liberated state, thereby increasing the proportion of gold accessible to flotation reagents. This hypothesis requires validation through systematic flotation testing before any engineering or economic assessment can be made. However, it must be acknowledged that the finest fractions ($-5 + 2 \mu\text{m}$ and $-2 \mu\text{m}$, representing 42.31% of total gold) are likely to remain predominantly locked regardless of grind size, as their full liberation would require sub-micron grinding that is neither technically practical nor economically feasible in an industrial circuit.

5.2. Detrimental Effects of Chlorite and Gangue Minerals

5.2.1. Chlorite as the Dominant Gold-Bearing Gangue

Another critical finding is the close association of the residual gold with chlorite (49.35%) and quartz (40.26%) (Figure 6). The particle-size-dependent liberation data (Table 6) further reveal that chlorite is the dominant locking mineral in the largest single size fraction ($-10 + 5 \mu\text{m}$), which accounts for nearly half (47.44%) of all gold grains. Among the 91.89% of locked gold in this fraction, chlorite hosts 88.2% of all locked gold grains (Table 7), confirming that the gold–chlorite association is not merely a bulk statistical feature, but is particularly pronounced in the size range most critical for liberation. Gold locked in hard quartz may be liberated by further size reduction, as quartz fractures readily along grain boundaries. In contrast, gold locked in soft chlorite is prone to remaining encapsulated, as chlorite preferentially deforms and smears rather than fracturing cleanly during grinding. Chlorite acts as the dominant gold-bearing gangue mineral due to its lamellar structure and strong adsorption capacity for fine gold [51], even though quartz is more abundant in the tailings overall.

5.2.2. Slime Coating: A Critical Barrier to Gold Flotation

Quartz is hard and relatively easy to grind, whereas chlorite presents a unique challenge. Chlorite is a soft, platy phyllosilicate mineral with a Mohs hardness of 2–2.5, much lower than 7 for quartz [52]. During intensive regrinding intended to liberate fine gold, chlorite preferentially overgrinds and generates a large amount of ultrafine slimes. Based on the well-documented behavior of phyllosilicate minerals in flotation [23,24,53], these chlorite slimes are highly likely to induce a deleterious "slime coating" effect, whereby fine, high-surface-area particles physically coat the surfaces of gold grains. This coating can act as a physical barrier, preventing collector adsorption and reducing gold hydrophobicity, thereby rendering it unfloatable.

Several lines of evidence from this study support the slime coating hypothesis, although none alone provides definitive proof.

First, the elevated oxygen contents (up to 8.31 wt%) detected in EDS spot analyses of some gold grains (Table 3) are not consistent with the composition of native gold. These oxygen signals are most plausibly attributed to the excitation of adjacent or adhering chlorite/muscovite particles, the epoxy mounting resin, or minor surface oxidation during sample storage and preparation.

Second, high-magnification BSE imaging directly revealed submicron-sized, low-backscatter-coefficient particles adhering to the surfaces of some larger gold grains (Figure

9). The morphology and backscatter contrast of these adhering particles are consistent with chlorite or other phyllosilicate minerals.

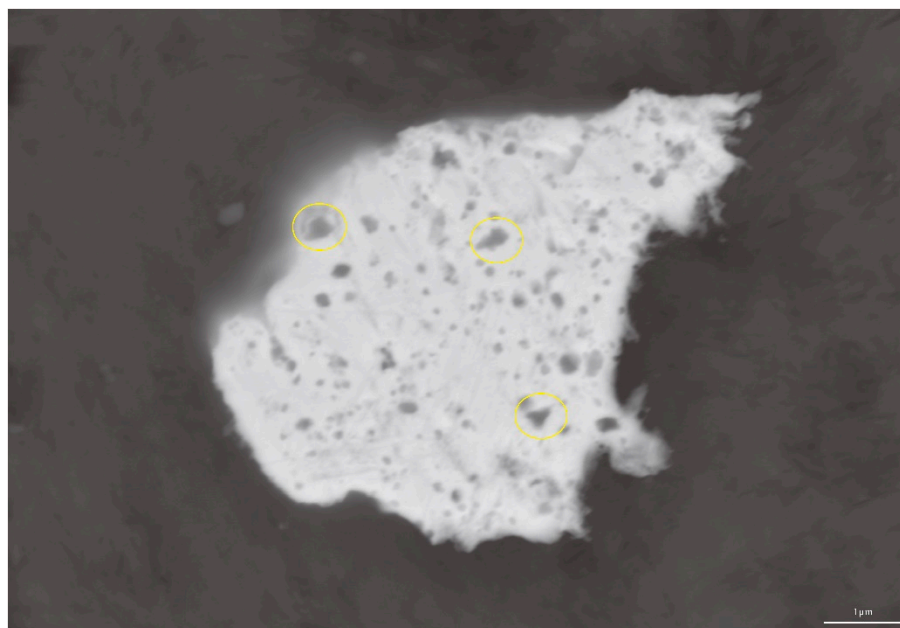


Figure 9. High-magnification BSE image of a gold grain surface in the Baolun tailings. Submicron-sized, low-backscatter-coefficient particles (circled) are chlorite, adhering to the gold surface.

Taken together, those observations—elevated oxygen in EDS spectra and direct morphological evidence from high-magnification BSE imaging—provide strong circumstantial evidence that fine chlorite particles are physically attached to gold grain surfaces. This is consistent with the well-known slime coating phenomenon documented in the flotation of phyllosilicate-rich ores.

Beyond the slime coating effect, abundant fine chlorite also increases pulp viscosity, consumes excessive flotation reagents, and reduces overall flotation selectivity [25]. As such, slime coating induced by overground chlorite likely represents a major detrimental factor restricting gold flotation recovery in the Baolun tailings.

5.2.3. Influence of Gold Particle Morphology on Flotation Recovery

The particle morphology data (Table 5) provide supplementary insight into the flotation challenges. Wheat-like and dendritic gold grains, which together constitute 33.33% of the total gold grain population, are characterized by high specific surface areas and complex surface roughness. These morphological features can exacerbate two issues relevant to flotation recovery. First, the large and irregular surfaces enhance the physical adhesion of chlorite slimes to gold grains, thereby amplifying the slime-coating effect discussed in Section 5.2.2. Second, their irregular shapes lower the collision probability with flotation bubbles and create unfavorable hydrodynamic drag during particle–bubble interaction, making attachment less stable and more susceptible to detachment under turbulent conditions [54,55]. The predominance of these problematic morphologies (one-third of all gold grains) further underscores the necessity of both controlled regrinding and effective slime management, as discussed in Section 5.3.

5.3. Implications for Process Optimization and Tailings Valorization

5.3.1. A Two-Pronged Strategy for Gold Recovery

The diagnosis suggests a two-pronged strategy for improving gold recovery from these tailings.

First, a regrind circuit would be required to reduce the liberation–grind size gap. Based on the particle-size-dependent liberation data (Table 6), we hypothesize that a regrind P80 in the range of 20–45 μm would be necessary to shift a meaningful portion of the gold currently in the $-37 + 10 \mu\text{m}$ and $-10 + 5 \mu\text{m}$ fractions toward a marginal or liberated state, thereby increasing the proportion of gold accessible to flotation reagents. This hypothesis requires validation through systematic flotation testing. However, as noted in Section 5.1.2, the finest fractions ($-5 + 2 \mu\text{m}$ and $-2 \mu\text{m}$, representing 42.31% of total gold) are likely to remain predominantly locked regardless of grind size.

The final choice of the regrind P80 must therefore be determined by a techno-economic trade-off analysis that weighs the incremental gold recovery value against the additional grinding energy and media costs. As an illustrative estimate, a Bond work index of 17.8 kWh/t was reported for a similar quartz-vein gold ore [56], suggesting that regrinding from P80 = 75 μm to 30 μm would likely involve substantial energy expenditure. The actual work index of the Baolun tailings should be determined experimentally before reliable economic projections can be made.

Second, and equally important, any regrinding strategy must actively mitigate the deleterious effects of chlorite slimes documented in Section 5.2. The addition of a gangue dispersant, such as sodium silicate or sodium hexametaphosphate, in the regrind mill or flotation conditioning tank is recommended [57–60]. The optimal dosage for the Baolun tailings should be determined through the systematic flotation test program. These dispersants adsorb onto the surfaces of chlorite slimes, imparting a strong negative charge that enhances electrostatic repulsion between chlorite and gold particles, thereby inhibiting the slime coating mechanism. This would help maintain clean, hydrophobic gold surfaces, facilitating collector adsorption and bubble attachment.

A systematic testwork program is recommended to validate this dual strategy and identify the techno-economically optimal operating conditions. Batch flotation tests are recommended, in which both the regrind size (e.g., P80 of 45, 38, 30, and 20 μm) and the dispersant dosage are varied. The primary response variables should include gold recovery, concentrate grade, and mass pull, with the objective of identifying the combination of grind size and dispersant dosage that maximizes the net economic return.

5.3.2. Towards Near-Zero-Waste Valorization

While this study focuses on gold recovery, the tailings are composed of 98% gangue minerals, with quartz accounting for 52.77%. Chemical analysis shows a SiO_2 content of approximately 72% (Table 1), suggesting that the tailings could be used as a raw material in the construction industry, such as in cement, concrete aggregates, or even as a feed for silicon-based materials. This utilization path has been supported by recent studies on quartz-rich tailings valorization [34]. Any future reprocessing flowsheet designed to recover gold should consider integrating subsequent steps to valorize the silicate fraction, moving towards a near-zero-waste objective.

5.3.3. Summary of Geometallurgical Diagnosis

In summary, this geometallurgical diagnosis provides a quantified explanation for gold loss in the Baolun quartz-vein gold tailings. The problem lies not simply in the presence of fine gold, but specifically in the combination of fine gold locked within a soft, easily over-ground gangue mineral—chlorite. The particle-size-dependent liberation analysis (Table 6) further reveals a critical physical limitation: 42.31% of the total gold resides in the $-5 + 2 \mu\text{m}$ and $-2 \mu\text{m}$ fractions, where complete mechanical liberation is practically unattainable. This finding underscores the necessity of the proposed dual strategy—controlled regrinding to liberate the coarser gold fractions, combined with chemical dispersants to manage the chlorite slimes that inevitably result from any regrind operation

and that would otherwise coat and render unfloatable the newly exposed gold surfaces. This evidence-based pathway for process optimization warrants further investigation through laboratory and pilot-scale testing.

6. Conclusions

1. Process mineralogical studies indicate that gold in the Hainan quartz-vein tailings occurs mainly as micro-fine native gold with an average grade of 0.44 g/t. Gold grains finer than 10 μm account for 89.74%, of which 92.31% are locked predominantly in quartz and chlorite. The finest fraction ($\sim 5\ \mu\text{m}$ and below), representing 42.31% of total gold, is almost fully locked, with chlorite as the dominant locking mineral. The insufficient liberation of gold from chlorite and quartz, particularly in the critical 2–10 μm size range, is the primary mineralogical cause of gold loss.
2. Improving gold recovery requires regrinding to liberate locked gold. However, complete mechanical liberation of the finest gold fractions is technically and economically unattainable. In addition, regrinding intensifies chlorite overgrinding, producing large amounts of ultrafine slimes that are highly likely to cause slime coating on gold surfaces, inhibiting collector adsorption and impairing flotation performance.
3. A two-pronged optimization strategy is proposed: (i) implement a regrind circuit with a target P80 of 20–45 μm to liberate the coarser gold fractions, though this requires validation through systematic flotation testing; (ii) add dispersants such as sodium silicate or sodium hexametaphosphate to mitigate chlorite slime coating and improve flotation selectivity. The optimal regrind size and dispersant dosage should be determined via techno-economic analysis and validated by laboratory and pilot-scale testing before industrial application.
4. The tailings contain 72% SiO_2 , with 98% gangue minerals dominated by quartz, indicating significant potential as a raw material for construction and industrial applications. Future reprocessing flowsheets should integrate gold recovery with silicate fraction valorization to strive towards a near-zero-waste objective.

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