

Article

Mineralogy and Pretreatment of a Refractory Gold Deposit in Zambia

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Abstract: The technological mineralogy of a gold deposit located in North-Western province of Zambia was carried out by using X-ray fluorescence spectroscopy (XRF), X-ray diffraction spectroscopy (XRD), and scanning electron microscope (SEM). The results showed that gold was highly dispersed in gold-bearing minerals such as pyrite, arsenopyrite, and some gangues in the form of natural gold and electrum. The gold grade in the mineral was 15.96 g/t and the particle size distribution of gold was extremely uneven. Most of the gold particles were less than 10 µm and wrapped with gold-bearing minerals, making it difficult to achieve liberation during grinding. According to the characteristics of the refractory gold deposit, the gravity–flotation combined beneficiation process was used to recover the liberated coarse gold and the fine gold in the sulphides. The closed-circuit experiments obtained excellent indicators. The grade and recovery of gold in the gravity separation concentrates reached 91.24 g/t and 57.58%, respectively. The grade and recovery of gold in the flotation concentrates were 49.44 g/t and 33.36%, respectively. The total recovery of gold was 90.94%. The gravity–flotation combined beneficiation pretreatment process provided a feasible method for the refractory gold ore and ensured the effective recovery of gold.

Keywords: gold deposit; mineralogy; gravity–flotation combined; pretreatment

1. Introduction

It is well known that gold is a precious metal and has been used as money, store of value, and jewelry for many centuries. The abundance of gold in the earth's crust is only three parts per billion [1]. With the rapid depletion of easy-to-treat gold deposits and in order to ensure the sustainability of resources, more attention has been paid to research on the recovery and utilization technology of refractory gold deposits [2,3].

The gold mineral should be pretreated before smelting due to the low grade of gold in the ore. The pretreatment process of gold mainly includes gravity separation, flotation, microbial oxidation, etc. [4,5]. Gold occurs usually in its native form or hosts in sulphides (especially pyrite, arsenopyrite, and chalcopyrite), silicate, carbonate, and oxide minerals [1,6,7]. Silver is generally associated with gold and it is usually recycled with gold [8,9].

The best pretreatment process is ultimately determined by the geological formation process and mineralogy of the gold deposit [10–13]. In general, liberated native gold is recovered by low cost gravity separation, especially for coarse gold [14,15]. Common gravity separation equipment includes shaking table, spiral chute, and jigging concentrator. The effectiveness of gravity separation equipment is closely related to the size and shape characterizations of gold particles [16–18]. The finer the grain size of gold particles, the more difficult they are to recover [18,19]. In sulphidic refractory gold ores, gold is highly disseminated and locked up in sulphide minerals, such as pyrite and arsenopyrite,

in the form of micro or sub-micro particles, and is often recovered with these sulphide minerals by flotation [8,20]. Thiol collectors such as xanthates and dithiophosphates are the most widely used flotation reagents in the gold mining industry, which increase the difference of hydrophobicity between sulfide and gangues [21,22]. Copper sulfate and sulfuric acid can activate pyrite and arsenopyrite and enhance their floatability so as to improve recovery of the gold deposit [23]. Gold-bearing pyrite and arsenopyrite account for a considerable proportion of refractory gold-bearing sulfide ores. Gold can be recovered through bulk flotation or selective flotation processes according to the distribution of gold in pyrite and arsenopyrite [24,25]. The selective flotation of arsenopyrite from pyrite can be realized by adding a magnesium–ammonium mixture depressant [26]. As we all know, arsenic is a highly toxic substance that causes great harm to the human body and the environment. If arsenic pyrite enters the gold smelting process, the arsenic is enriched and the flow direction is difficult to control, making it more difficult to handle. If the associated relationship between gold and arsenopyrite is not tight and does not affect the gold recovery rate, the best method for removing arsenic is to discharge it into the tailings through a selective flotation process to ensure that arsenic is relatively stable and at a lower state [27–29]. Cyanide leaching is a traditional and methodically developed process, which is effective for extracting gold from refractory ores [30]. However, cyanide has gradually been replaced by other lixiviants such as glycine and thiourea because of its strong toxicity and serious environmental damage [31–33]. Nowadays, more and more new biological approaches are being studied to recover gold from refractory gold-bearing sulfide ore [5,34–36]. Although biometallurgy is environmentally friendly, it has not been applied on a large scale because its production cycle is too long and the environmental requirements of bacteria are strict [37,38].

A gold deposit containing pyrite and arsenopyrite invested in by Chinese companies is located in North-Western province in Zambia. The gold is pre-enriched by the method of beneficiation, and the obtained gold concentrate is transported back to China to recover gold by metallurgical method. In order to reduce subsequent transportation costs and metallurgical costs, it is desirable to pre-enrich the gold ore using a suitable pretreatment process. The gold grade in the raw ore is relatively high, as shown in Table 1. Systematic laboratory study of the mine was not conducted due to the local conditions. In the actual production process, regardless of the pretreatment process using gravity separation of shaking table or flotation, the gold recovery cannot achieve the expected indicators. At the same time, the high arsenic content in gold concentrates increases the environmental pressure of subsequent treatment processes. Therefore, this paper aims to characterize the high-sulfur and high-arsenic gold deposit and understand the chemical element composition, the mineralogical composition, and intercalation of minerals, especially the state of gold occurrence by process mineralogy. According to the results of process mineralogy, the reasons for the low efficiency of beneficiation and the possibility of removing arsenic from gold concentrate are analyzed, and a suitable pretreatment process is proposed to recover the refractory gold ore reasonably and efficiently.

Table 1. Chemical analysis of the raw ore (mass fraction, %).

S	Fe	Cu	Zn	As	Sb	Pb	Ag *	Au *
7.91	15.44	0.05	0.33	6.50	0.12	0.42	123.64	15.96

* The units of Au and Ag are g/t.

2. Materials and Methods

2.1. Mineral Samples

The samples used in this study were obtained from an arsenic-containing sulfur-bearing gold deposit in North-Western province, Zambia. The representative sample taken was mixed proportionally with the ore samples at each mining point. A bulk sample of 150 kg crushed to −2 mm was homogenized

and split into 500 g representative sub-samples. The results of chemical analysis of raw ore are shown in Table 1. The content of gold in the ore was 15.96 g/t.

2.2. Methods

2.2.1. Mineralogical Study

The contents of different elements of the ore were tested by X-ray fluorescence (XRF, S0902724, Rigaku, Tokyo, Japan). The mineralogical composition and content of the ore were identified by X-ray diffraction (XRD, S0902240, Rigaku, Tokyo, Japan). The mineral paragenesis and size distribution were analyzed by scanning electron microscope (SEM, JSM-6360LV, JEOL, Tokyo, Japan), energy dispersive spectrometer (EDS, EDX-GENESIS, Ametek, Berwyn, PA, USA), electron microprobe analysis (EMPA, 1720H, Shimadzu, Japan), polarizing microscope (LEICA DM4500P, Germany), and other conventional analysis.

2.2.2. Gravity Separation and Flotation

Samples of 500 g with a particle size of 100% passing 2 mm were ground in a closed stainless steel $\varnothing 240 \times 90$ mm² XMQ conical ball mill (Wuhan Exploring Machinery Plant, Wuhan, China) at a slurry concentration of 66% (mass concentration). Gravity separation tests were carried out on a LY-1100 $\times$ 500 shaking table (Wuhan Exploring Machinery Plant, Wuhan, China). Flotation experiments were carried out using an XFD series single flotation cell (Jilin Exploring Machinery Plant, city, China) with volumes of 1.5 L, 1 L, and 0.5 L for rougher, scavenger, and cleaner flotation, respectively. Flotation experiments were conducted at a solid content of 25–40%. The flotation reagents were added to the cell and stirred for several minutes before rougher, scavenger, and cleaner flotation.

2.3. Reagents

Flotation experiments were carried out using sodium silicate, copper sulfate, and carboxymethocel (CMC) as regulators and terpinol as frother. The collectors contained sodium butyl xanthate (SBX) and ammonium dibutyl dithiophosphate (ADD). All flotation reagents were acquired from Hunan Mingzhu flotation reagents limited company (Zhuzhou, China). All of these reagents were industrial grade and were diluted in water to a concentration of 1–5% before being added to the flotation tank.

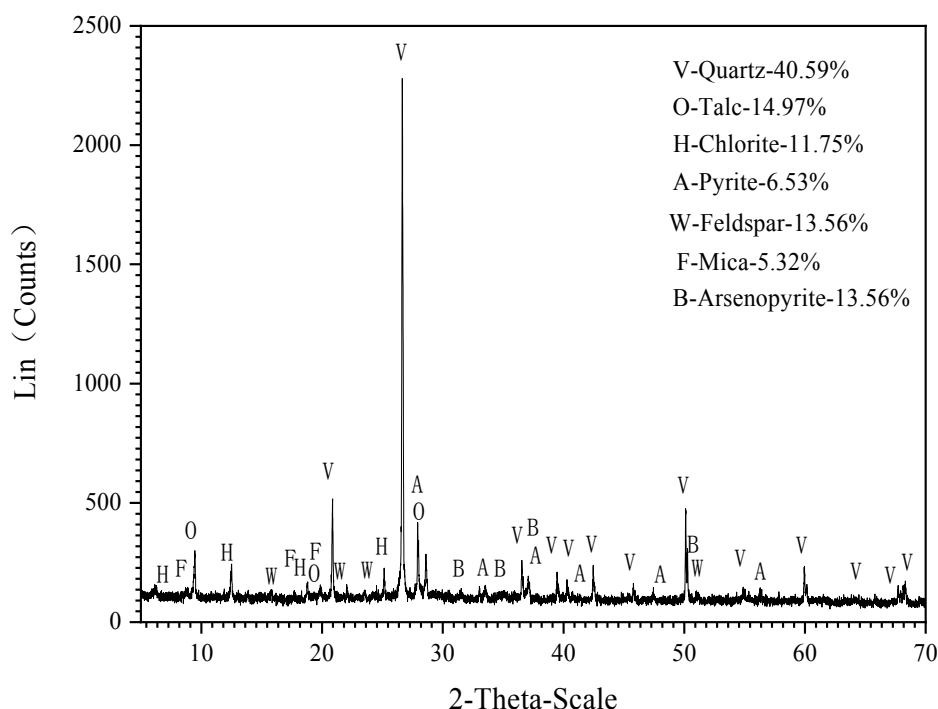
3. Results and Discussion

3.1. Composition and Content of Ore

The modal mineralogy of the ore was mainly green schist. The key minerals were chlorite, mica, talc, and so on. Major alterations were silicification and pyrite mineralization. The results of chemical composition of the ore determined by XRF are listed in Table 2. It can be seen that the other valuable metals in the ore were Ag, Zn, and Pb. The main non-metallic element was Si. Figure 1 shows the XRD pattern of raw ore. The XRD quantitative analysis results indicated that the contents of quartz, talc, chlorite, pyrite, feldspar, mica, and arsenopyrite in the ore were 40.59%, 14.97%, 11.75%, 6.53%, 13.56%, 5.32%, and 13.56%, respectively. Gangue minerals were mainly quartz, chlorite, feldspar, talc, and mica.

Table 2. Element analysis of samples by XRF (mass fraction, %).

Mg	Al	Si	S	K	Ca	Ti
3.921	4.785	31.145	4.076	0.824	0.321	0.133
V	Cr	Mn	Fe	Ni	Cu	Zn
0.018	0.232	0.02	8.783	0.069	0.04	0.294
As	Sr	Ag	Sb	Pb		
4.99	0.005	0.011	0.124	0.388		

**Figure 1.** XRD pattern of raw ore.

The samples with a particle size of 73% passing 74 μm were used for phase analysis. Table 3 shows the result of chemical phase analysis of gold in the ore. It demonstrates that gold mainly existed in the form of native gold or was distributed in pyrite, arsenopyrite, and other oxides. Gold in native gold and sulphides accounted for 88.82%.

Table 3. Chemical phase analysis of gold in ore.

Phase	Native Gold	Gold in Pyrite and Arsenopyrite	Gold in other Sulphides	Gold in Oxides	Other	Total
Content ($\text{g}\cdot\text{t}^{-1}$)	10.82	2.90	0.42	1.67	0.11	15.92
Distribution (%)	67.96	18.22	2.64	10.49	0.69	100.00

3.2. Occurrence of Main Metallic Minerals

3.2.1. Gold

Gold mainly appeared in the form of natural gold and electrum in the ore. As the amount of silver in the gold increased, the color of gold under the microscope changed from golden yellow to bright yellow. Gold mainly occurred in the form of enclosing gold, fracture gold, and intergranular gold in pyrite, arsenopyrite, sphalerite, jamesonite, and gangues.

Gold in Pyrite

Pyrite was closely related with gold and was the main gold-bearing mineral. Gold was more likely to appear in the better crystallized pyrite. It could be seen that most of the gold was enclosed in pyrite by irregular, granular, strip, and a small amount of gold was distributed in cracks and holes in pyrite under the microscope. Most gold particles had a particle size of less than 10 μm . Very few large particles of gold reached 50 to 60 μm , and fine particles below 1 μm of gold particles accounted for a certain proportion. It was difficult to dissociate gold particles by grinding. Figure 2 shows images of gold in pyrite under reflected light.

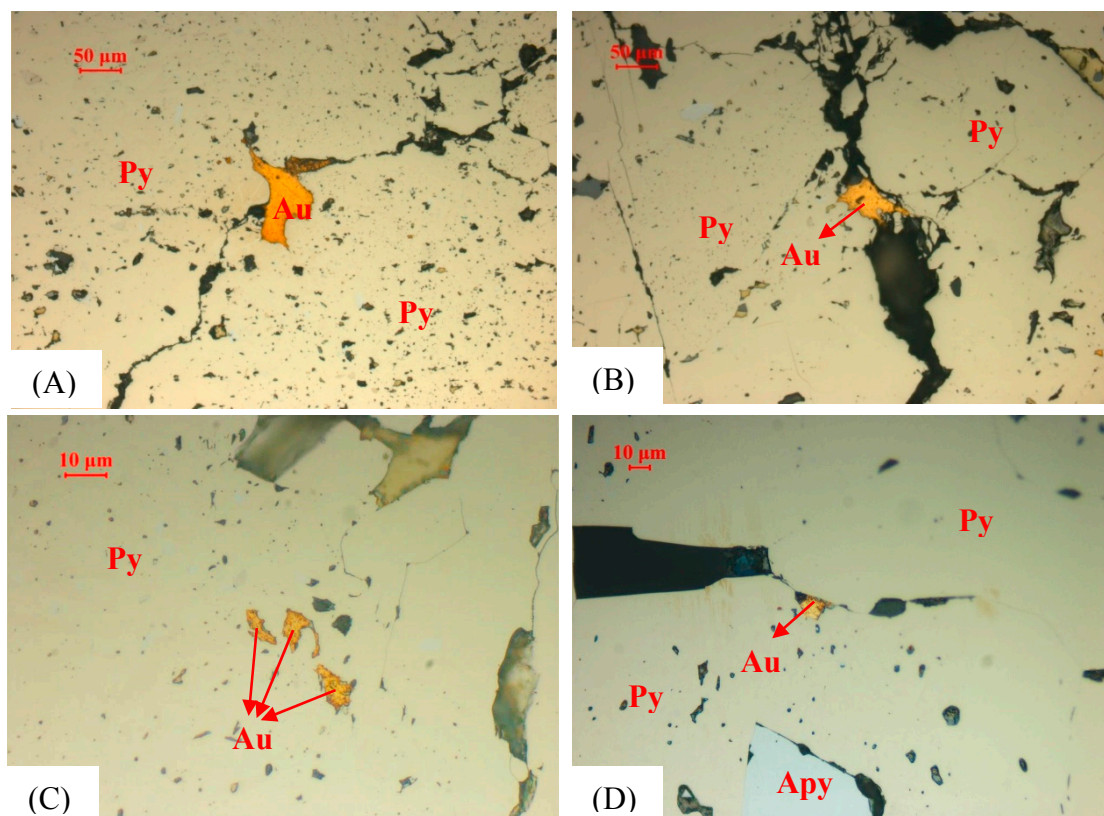


Figure 2. Images of gold in pyrite in reflected light: (A) enclosing gold in pyrite; (B) intergranular gold in pyrite; (C) enclosing gold in pyrite; (D) fracture gold in pyrite (Py—pyrite; Apy—arsenopyrite; Au—gold).

Figure 2A,B shows that gold with larger particles embedded in pyrite in an irregular shape and some fine gold particles with sizes between 3 μm and 10 μm were distributed around the large gold particles under the microscope. The long diameter of the larger gold particles in Figure 2A was 60 μm . Figure 2C,D shows the enclosing gold and fracture gold of the finer particles in the pyrite, respectively.

Figure 3A,B shows the SEM image and EDS analysis of large particle gold in Figure 2A,B, respectively. The results of EDS indicated that the content of Au in the gold particles was 98.02% in Figure 2A and the Au content was 72.20% and the Ag content in the gold particles was 27.80% in Figure 2B.

Gold in Arsenopyrite

Arsenopyrite was also the main gold-bearing mineral and it was closely related with gold. The distribution of gold in arsenopyrite was similar to that in pyrite. Most of the fine-grained gold with a particle size of less than 10 μm was highly dispersed in arsenopyrite, as shown in Figure 4A. The long diameter of the inclusive gold, as seen in Figure 4A, was about 10 μm . Figure 4B shows

the large grain of gold distributed in the arsenopyrite hole. When the ore was crushed and ground, the hole may have been split and the gold was dissociated. Figure 5 shows SEM images and EDS analysis of intergranular gold in arsenopyrite. The result indicated that the Au content of gold particles was 72.27%, and the Ag content was 27.73%. The As content was 38.79%, S content 24.29%, and Fe content 36.92% of arsenopyrite around gold particles.

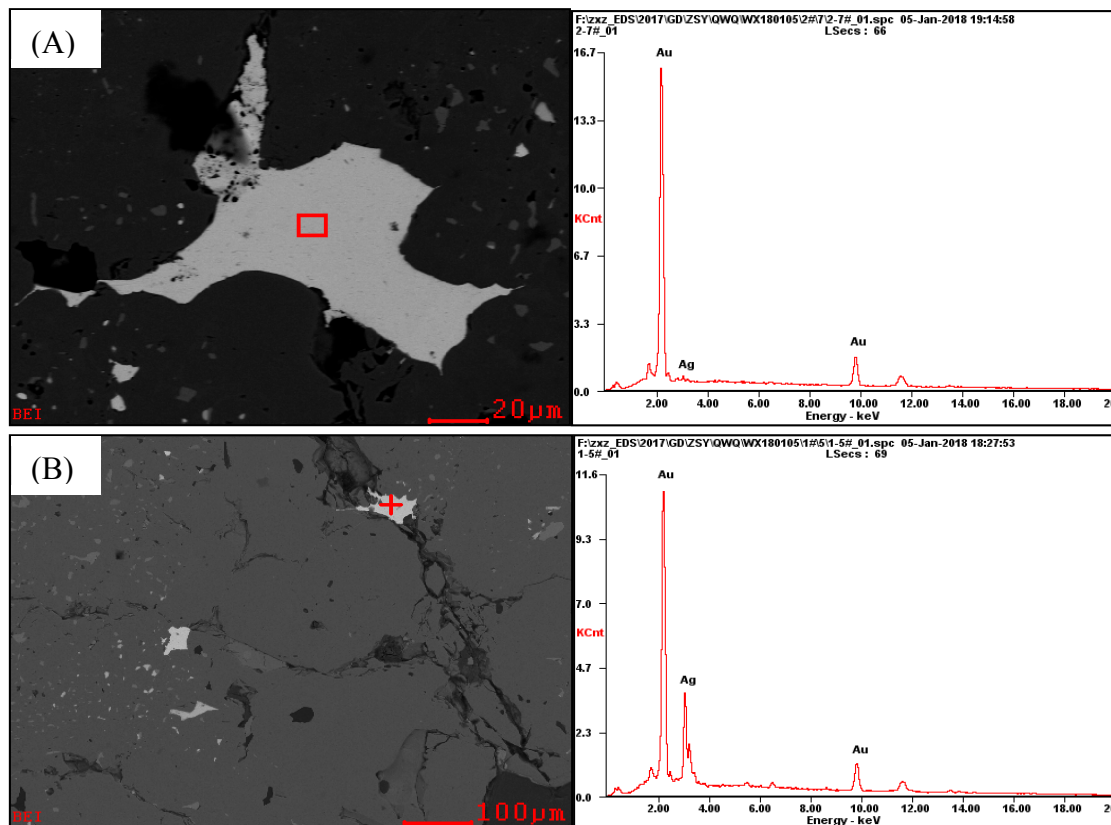


Figure 3. SEM images and EDS analysis of gold in pyrite: (A) enclosing gold in pyrite; (B) intergranular gold in pyrite.

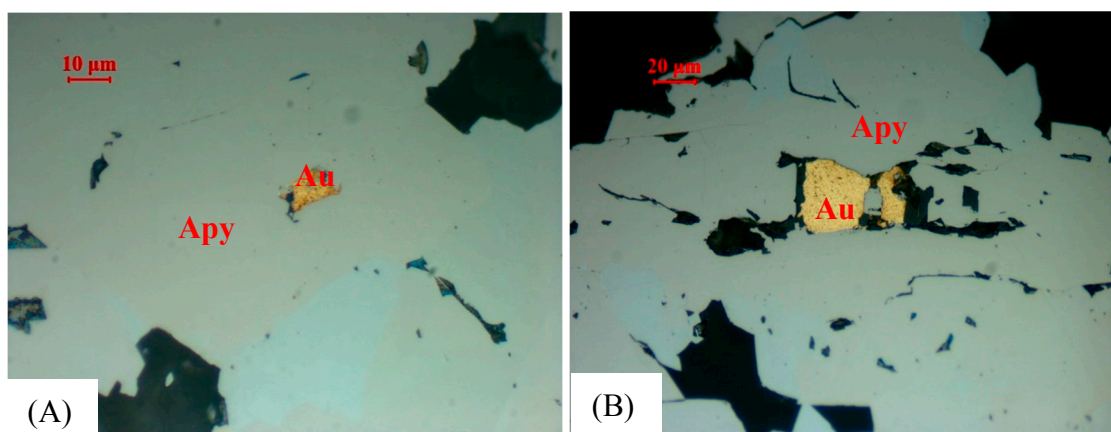


Figure 4. Images of gold in pyrite in reflected light: (A) enclosing gold in arsenopyrite; (B) hole gold in arsenopyrite (Apy—arsenopyrite; Au—gold).

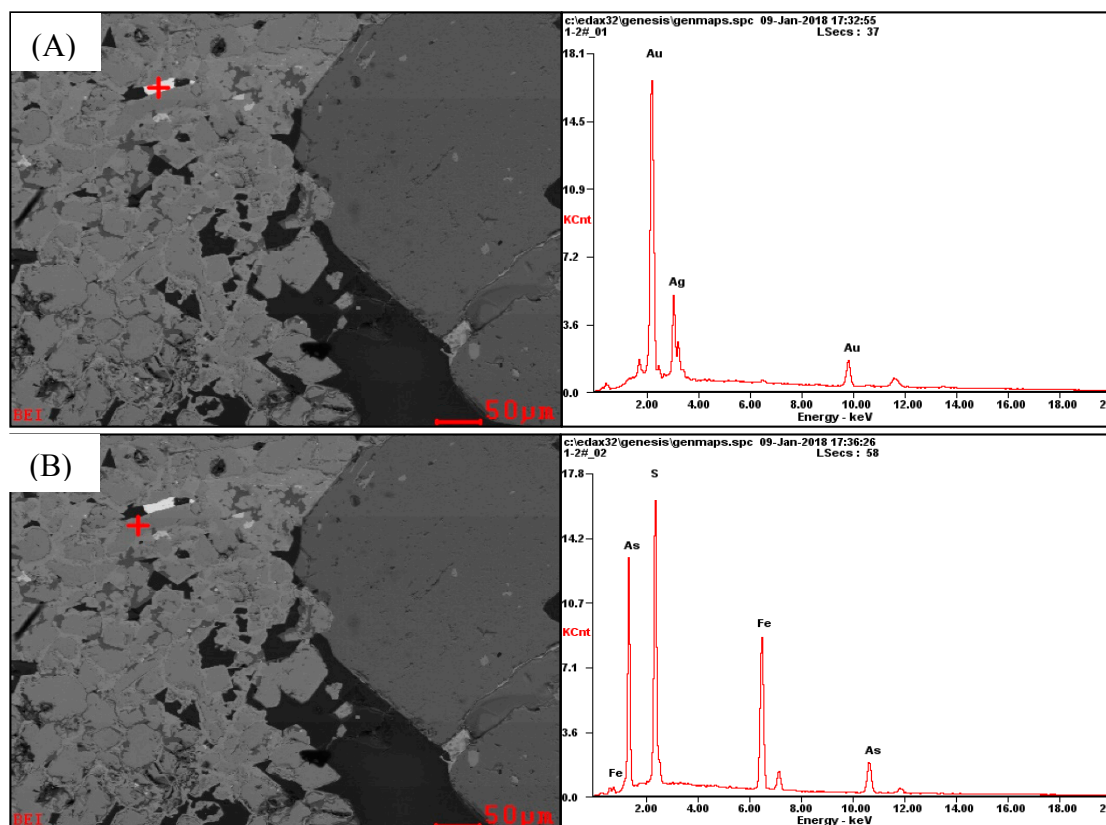


Figure 5. SEM images and EDS analysis of intergranular gold in arsenopyrite: (A) enclosing gold in arsenopyrite; (B) arsenopyrite.

Gold in other Minerals

In addition to the gold distributed in pyrite and arsenopyrite, a small amount of gold was distributed in other sulphides and gangues. Figure 6 shows images of gold in other minerals in reflected light. Gold was mainly distributed at the edge of galena, jamesonite, and sphalerite. The gold in the gangue was distributed in a granular or irregular shape. The coarse gold particles in gangue were about 40 μm, and the fine particles were 3–5 μm. Gold particles in the holes of gangue might have fallen off during grinding.

3.2.2. Pyrite and Arsenopyrite

Pyrite and arsenopyrite were the main sulfides in the ore. The pyrite particle size distribution in the ore was uneven, and it existed in the form of self-crystal, semi-self-crystal, and other crystals. There were many holes and cracks inside the pyrite particles. Figure 7A,B indicates that the ore contained coarse-grained arsenopyrite and fine-grained arsenopyrite. The coarse-grained arsenopyrites were cemented together to form a massive aggregate, and fine-grained arsenopyrites were cemented together to form a dense aggregate. The pyrite and arsenopyrites were closely related to each other in the ore. As shown in Figure 7D, the fine-grained arsenopyrite cemented pyrite formed a dense structure, making it difficult to separate by grinding. The intergranular pores of arsenopyrite were often cemented with sphalerite and galena. At the same time, arsenopyrite and pyrite were also distributed in other sulfide minerals.

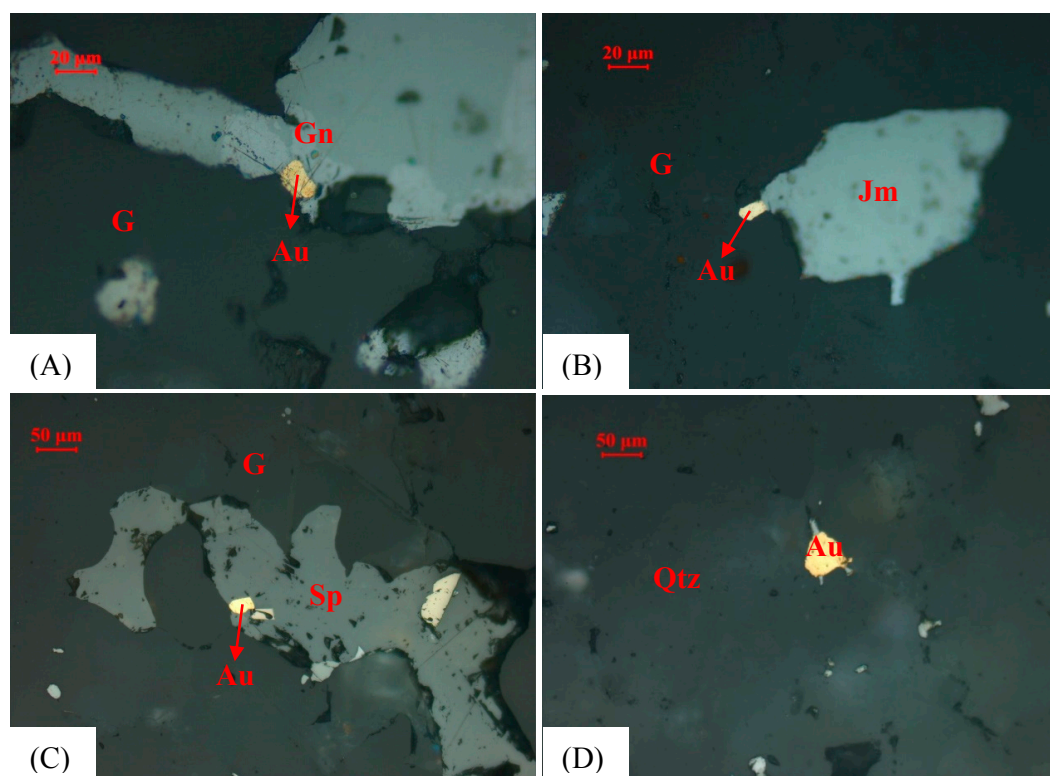


Figure 6. Images of gold in other minerals in reflected light: (A) gold associated with galena; (B) gold associated with jamesonite; (C) gold associated with sphalerite; (D) gold associated with quartz (Au—gold; Gn—galena; Jm—jamesonite; Sp—sphalerite; Qtz—quartz; G—gangue).

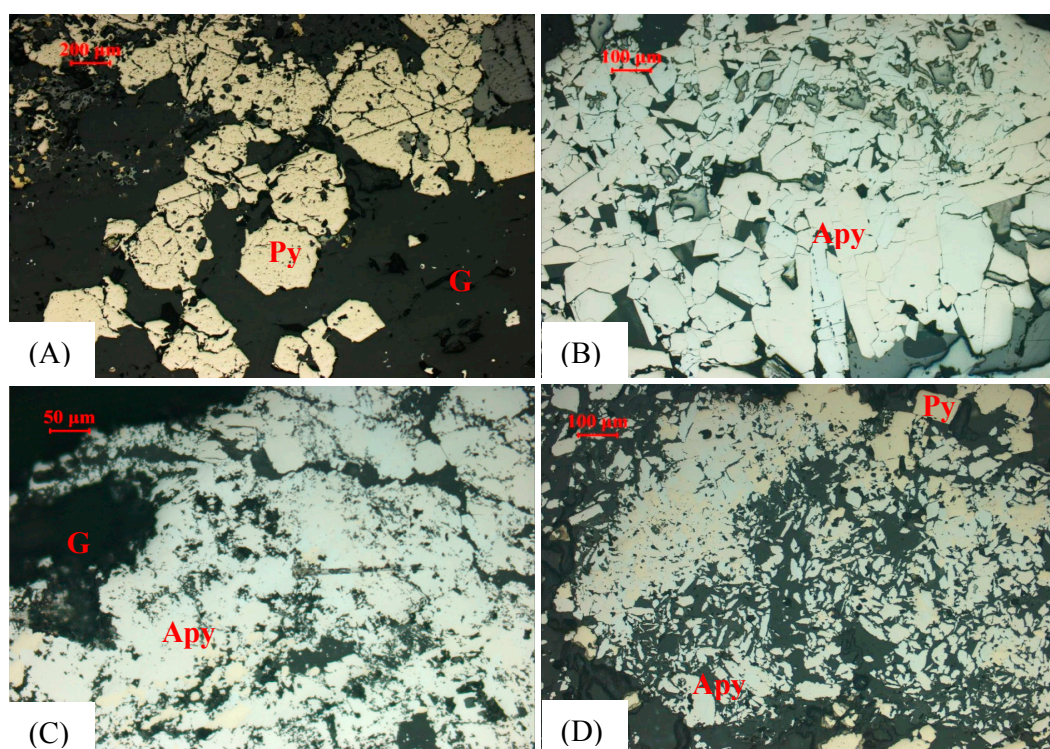


Figure 7. Images of pyrite and arsenopyrite in reflected light: (A) pyrite; (B) coarse arsenopyrite aggregate; (C) fine arsenopyrite aggregate; (D) an aggregate of pyrite and arsenopyrite (Py—pyrite; Apy—arsenopyrite; G—gangue).

3.2.3. Other Sulphides

The metallic elements Zn, Pb, Sb, and Cu in ore mainly occurred in the form of sphalerite, galena, jamesonite, and chalcopyrite. Figure 8A shows an image of an aggregate of sphalerite, jamesonite, and chalcopyrite, and Figure 8B shows an image of galena in reflected light of the microscope. The sphalerite was closely associated with chalcopyrite, and the galena ore was closely associated with jamesonite in the ore. Galena and jamesonite were usually in the form of symbionts with uneven grain size distribution in the ore. Some arsenopyrite was distributed in jamesonite in granular form.

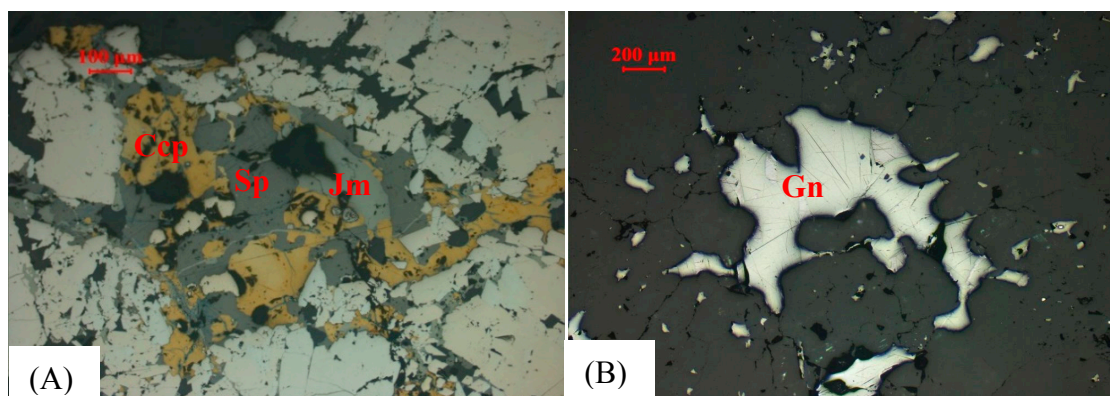


Figure 8. Images of other sulphides in reflected light: (A) aggregate of sphalerite, jamesonite, and chalcopyrite; (B) image of galena (Sp—sphalerite; Ccp—chalcopyrite; Jm—jamesonite; Gn—galena).

3.3. Strategies to Recover Gold

The results of the mineralogy study showed that gold in the ore mainly existed in the form of natural gold and electrum. Pyrite and arsenopyrite were the main gold-bearing minerals, followed by sphalerite, galena, jamesonite, and some gangue minerals. Gold particles of 5–10 µm were most distributed in the ore, followed by the particle size less than 1 µm, which accounted for a certain distribution rate. The largest particle size of about 100 µm accounted for a very small part. The results of EDS indicated that the Au content of gold particles varied from 30 to 98%. Gangue minerals were mainly quartz, chlorite, feldspar, talc, and mica. Most of the fine-grained gold distributed in pyrite and arsenopyrite was mostly completely encapsulated, and it was difficult to dissociate. In addition, there was some gold in granular, irregular form distribution in quartz and other gangue minerals. The associated relationship between pyrite and arsenopyrite was also extremely close.

According to the results of mineralogy study, gold particles had a wide range of particle size distribution. The natural gold in gangue and the coarse-grained gold dissociated from sulphide ore could be recovered by gravity separation. However, the fine-grained gold associated with sulphides was difficult to be enriched and recovered by gravity separation. This might be the reason for the low efficiency of gravity separation in actual production. The gold associated with sulphides or fine-grained gold could be enriched into sulphide concentrate to the maximum extent by flotation. However, flotation has a poor recovery effect on coarse-grained gold. At the same time, the layered silicate minerals such as chlorite and talc had good natural floatability, and they were easily floated with the sulfide ore, which might lead to a decline in concentrate grade [39]. This might be the reason for the poor efficiency of flotation in actual production. Since some fine-grained grade gold was highly dispersed in arsenopyrite, and the associated relationship between pyrite and arsenite was extremely close, the removal of arsenic during the beneficiation process would reduce the recovery rate of gold. The nature of the ore determined that the gold mine did not have the innate conditions for arsenic removal during the beneficiation process. Therefore, the gold mine was a refractory gold deposit containing arsenic and sulfur.

In this refractory gold deposit, gold particles that were dissociated from the gangue and sulfide monomers after grinding could be recovered by gravity beneficiation. The fine-grained gold still

encased in pyrite and arsenite was recovered by bulk flotation. Therefore, the gravity–flotation combined beneficiation pretreatment process might be a reasonable way to recover gold from ore. Figure 9 shows the flow chart of the gravity–flotation combined beneficiation.

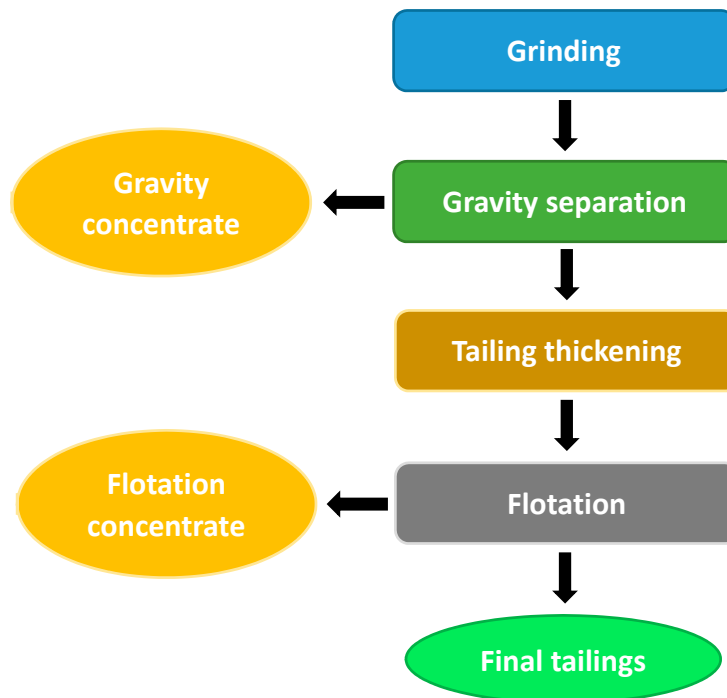


Figure 9. The flow chart of gravity–flotation combined beneficiation.

3.4. Gravity Separation

According to the conditions of the site, the shaking table was used as gravity separation equipment to treat this refractory gold ore. The efficiency of the shaking table on recovering coarse gold particles was better than other gravity separation equipment, and it had less pollution to the environment. The effects of grinding fineness and number of gravity separations on the index of gravity separation concentrate were investigated. The ball mill process parameters were: steel ball filling rate of 33%, grinding amount of 500 g, and pulp density of 66 wt.%. The process parameters of the shaking table were: 20 kg/h of processing capacity, 20 wt.% of pulp density, 0.65° of lateral gradient, 400 L/h of horizontal flush water, 16 mm of stroke, and 450 min^{−1} of stroke frequency.

The experiment results are shown in Figure 10. Figure 10A indicates that with increase of grinding fineness, the gold grade gradually increased, and the gold recovery to raw ore gradually decreased in the one-stage gravity separation concentrate. After the grinding fineness of −0.074 mm exceeded 73.56%, the gold grade did not rise any more, and the recovery rate of gold did not change much. This also indicated that after the ore reached a certain fineness, the coarser gold particles were substantially dissociated, and the fine particle gold was difficult to achieve monomer dissociation. Therefore, the grinding fineness of −0.074 mm was tentatively determined to be about 73%, and the grinding time was 2 min 15 s. The characteristics of the grinding products, as seen in Table 4, indicated that 88.94% of the gold was distributed below 0.074 mm.

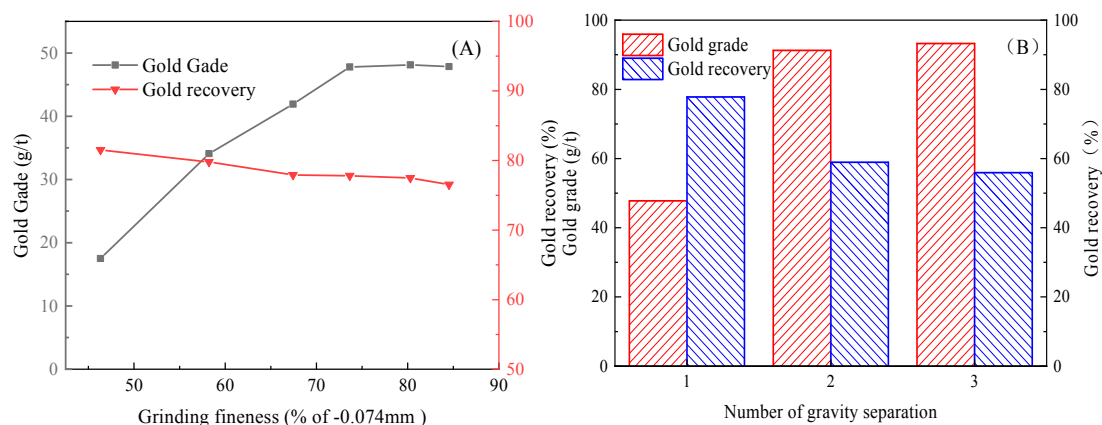


Figure 10. The results of gravity separation as a function of grinding fineness (A); and as a function of the number of gravity separations (B).

Table 4. The characteristics of the grinding products.

Particle Size (mm)	Yield (%)	Grade (%)				Distribution Rate (%)			
		Au *	As	S	Fe	Au	As	S	Fe
−2.00 + 0.15	1.84	8.67	4.66	6.03	8.11	1.01	1.44	1.45	2.24
−0.15 + 0.106	17.57	5.01	2.41	5.24	4.31	5.55	7.11	12.04	11.37
−0.106 + 0.074	6.87	10.40	4.81	7.94	5.43	4.50	5.55	7.13	5.60
−0.074 + 0.038	31.68	16.83	5.06	6.79	4.82	33.62	26.87	28.10	22.92
−0.038	42.04	20.87	8.37	9.33	9.17	55.32	59.03	51.28	57.87
Total	100.00	15.86	5.96	7.65	6.66	100.00	100.00	100.00	100.00

* The unit of Au is g/t.

The gravity concentrate was subjected to multiple gravity separations after adjusting the height of the table surface. The gold grade of gravity concentrates increased, and the gold recovery decreased with the increasing of number of gravity separations. Since the difference of the index between the two-stage gravity separation and the three-stage gravity separation was not obvious, the number of gravity separations of the shaking table was set at two-stage. The gold grade in the gravity concentrate was about 90 g/t, and the gold recovery rate was about 58%.

3.5. Flotation Separation

The tailings of two stage gravity separation were combined and thickened for flotation feed. The reagent regimes of roughing were investigated, and the results are shown in Figure 11.

The effect of the dosage of sodium silicate on rougher flotation was investigated. The results are presented in Figure 11A. The dosages of other flotation reagents were fixed at 50 g/t of CuSO_4 , 150 g/t of SBX, and 20 g/t of terpenol. It can be seen from Figure 11A that with the increase of the dosage of sodium silicate, the gold grade in the flotation coarse concentrate gradually increased, and the recovery rate of gold to the ore gradually decreased. As predicted, a large number of gangues floated during the roughing process, resulting in a decrease in flotation efficiency. The foam was rich and sticky and difficult to combine. After filtration and drying, it could be clearly seen that there were more talc and chlorite in the coarse concentrate. Continuously increasing the dosage of sodium silicate did not effectively depress chlorite and talc. The dosage of sodium silicate was tentatively set at 2000 g/t.

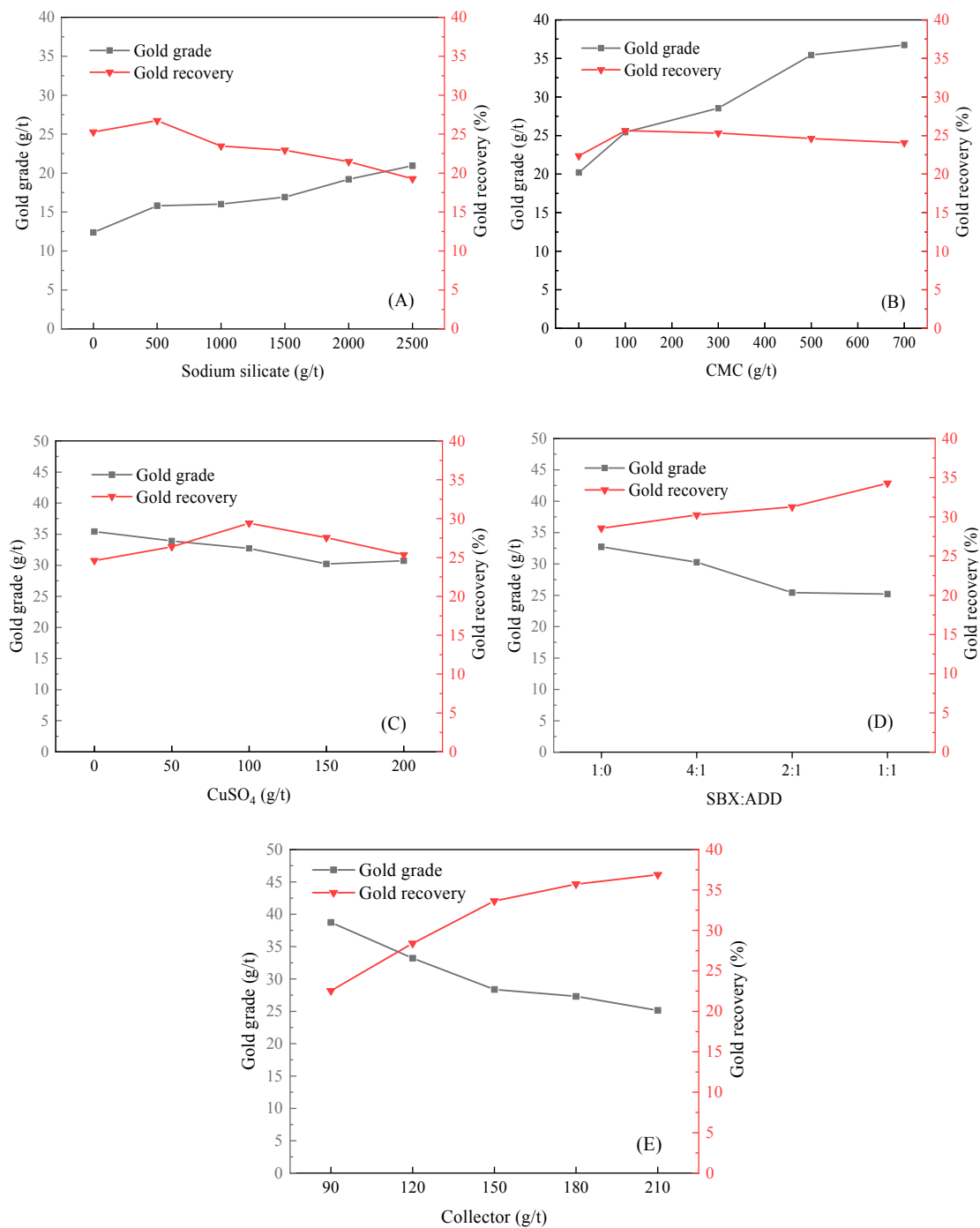


Figure 11. Effects of operating parameters on flotation recovery: (A) sodium silicate dosage, (B) CMC dosage, (C) CuSO₄ dosage, (D) the ratio of SBX and ADD, (E) collector dosage.

CMC has a large molecular weight and a high degree of molecular structure branching and bending. It not only formed a hydrophilic layer on the mineral surface, but also covered up the mineral surface that had formed a hydrophobic layer and a strong inhibiting capacity [40,41]. The addition of CMC enhanced the inhibition of chlorite and talc. The results of the CMC dosage test are shown in Figure 11B. The dosages of other flotation reagents were fixed at 2000 g/t of sodium silicate, 50 g/t of CuSO₄, 150 g/t of SBX, and 20 g/t of terpinolol. The results indicated that with the increase of CMC dosage, the gold grade in the coarse concentrate was significantly improved, and the recovery rate of gold decreased less. After the dosage of CMC reached 500 g/t, the gold grade in the coarse concentrate increased slightly, so the dosage of CMC was set to 500 g/t.

Copper sulphate can activate pyrite and arsenopyrite to promote gold recovery in the flotation process. The results of the investigation on the effect of the dosage of CuSO_4 on the recovery of gold are shown in Figure 11C. The dosage of other flotation reagents were fixed at 2000 g/t of sodium silicate, 500 g/t CMC, 50 g/t of CuSO_4 , 150 g/t of SBX, and 20 g/t of terpenol. As the dosage of CuSO_4 was increased, the gold grade decreased slightly, and the recovery rate of gold gradually increased. When the dosage of CuSO_4 exceeded 100 g/t, the recovery of gold decreased because the collector was consumed by excess copper ions. The dosage of copper sulfate was set to 100 g/t.

SBX and ADD are often used together to increase the recovery of gold ore. ADD has a certain foaming property and a relatively strong collecting ability. The test results of the mixture ratio of SBX and ADD are shown in Figure 11D. The dosages of flotation reagents were fixed at 2000 g/t of sodium silicate, 500 g/t CMC, 100 g/t of CuSO_4 , 150 g/t of collector, and 20 g/t of terpenol. When SBX and ADD were combined as a collector at a ratio of 1:1, the recovery of gold was nearly 6% higher than that of SBX alone, and the gold grade was reduced by nearly 7 g/t. In order to recover gold resources as much as possible, priority was given to the recovery rate of gold, and the ratio of SBX and ADD was set to 1:1.

The test results of the mixed collector dosage are presented in Figure 11E. The dosages of other flotation reagents were fixed at 2000 g/t of sodium silicate, 500 g/t CMC, 100 g/t of CuSO_4 , and 20 g/t of terpenol. As the dosage of the collector increased, the recovery rate of gold gradually increased, and the grade of gold gradually decreased. When the dosage of the collector was 210 g/t, the flotation foam was sticky and it was not conducive to cleaner flotation. In general, the optimum dosage of the collector was 180 g/t, and all subsequent experiments were performed with this dosage.

3.6. Closed-Circuit Beneficiation Test

The closed-circuit flow test was carried out on the basis of the condition tests of the gravity separation and flotation. The process is shown in Figure 12, and the test results are shown in Table 5. The results indicated that the gold grade was 91.24 g/t and the gold recovery was 57.58% in the gravity concentrate. The gold grade was 49.44 g/t and the gold recovery was 33.36% in the flotation concentrate, and the total recovery of gold was 90.94%. The main minerals in the flotation concentrate were pyrite and arsenopyrite, the total content of As, S, and Fe reached 88.30%, and the further enrichment space of gold in the gold-bearing mineral was limited by flotation.

Table 5. The results of the closed-circuit test.

Product	Yield (%)	Grade (%)				Recovery (%)			
		Au *	As	Fe	S	Au	As	Fe	S
Gravity concentrate	10.52	91.24	21.31	38.18	35.07	57.58	42.62	38.11	46.00
Flotation concentrate	11.25	49.44	18.36	36.36	33.58	33.36	39.27	38.81	47.10
Tailing	78.23	1.93	1.22	3.11	0.71	9.06	18.11	23.08	6.89
Feed	100.00	16.67	5.26	10.54	8.02	100.00	100.00	100.00	100.00

* The unit of Au is g/t.

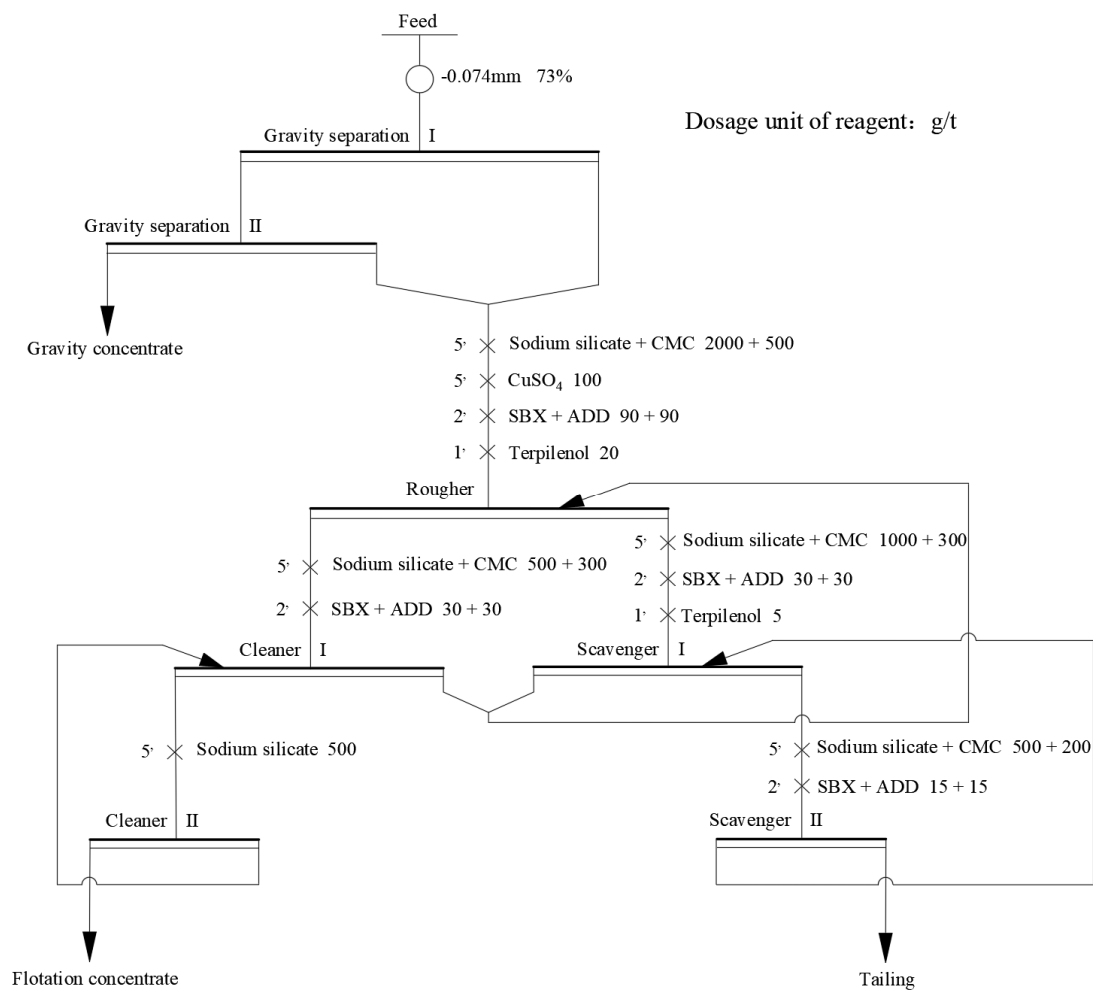


Figure 12. Image of closed-circuit combination process of gravity separation and flotation.

4. Conclusions

(A) The results of the processing mineralogy study showed that the gold grade in the ore was about 15.96 g/t, and the gold mainly existed in the form of natural gold and electrum. The main gold-bearing materials were pyrite, arsenopyrite, and some gangues. The gold particles were uneven, and most of them were fine grains of 5–10 μm . Other metallic minerals in the ore included sphalerite, galena, and jamesonite, and gangue minerals included quartz, mica, feldspar, talc, and chlorite.

(B) Fine-grained gold, which was highly dispersed in the ore-bearing minerals, and the large amount of stratified silicate minerals were the main reasons for the poor pretreatment effect of the refractory gold ore whether it was gravity separation alone or flotation alone. Fine-grained gold in arsenopyrite is difficult to dissociate, and the removal of arsenic during the beneficiation process will lead to a decrease in gold recovery.

(C) According to the research results of the processing mineralogy study, the gravity–flotation combined beneficiation process was used to pretreat the refractory gold deposit, and the coarse gold particles and fine gold particles in sulphides were recovered, respectively. The index of the closed-circuit test of the gravity–flotation combined beneficiation was that the gold grade was 91.24 g/t and the gold recovery was 57.58% in the gravity concentrate, the gold grade was 49.44 g/t and the gold recovery was 33.36% in the flotation concentrate, and the total recovery of gold was 90.94%. This indicated that gravity–flotation combined beneficiation was an effective pretreatment method for this refractory gold ore. The effect of the gravity–flotation combined process was superior to the gravity beneficiation process and the flotation process, and the cost was lower than the full-process flotation.

(D) Limited by the occurrence of the refractory gold deposit, the gold concentrate obtained is difficult to be further enriched through the method of beneficiation. The gold concentrate obtained by this process will eventually be shipped back for metallurgical processing to obtain gold.

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