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# Influence of mineralogy of low grade refractory Au ore on processing and blending strategy

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**Abstract:** Gold recoveries can be low when refractory gold-bearing ores are subjected to direct cyanide leaching, so pre-treatment processes may be required prior to leaching. In this study, drill core samples from a refractory gold ore deposit were mineralogically characterized and three main zones were defined as sulfide, transition, and oxide. Native gold occurs in association with pyrite in the sulfide and transition zones, while in the oxide zone it has been found to be sub-microscopic size and associated with FeOx minerals. The Au contents were determined as 1.13 ppm, 0.71 ppm and 0.76 ppm in sulfide, transition, and oxide zones, respectively. Bottle-roll tests indicated that the ore deposit can be classified as refractory with average Au recoveries for the sulfide, transition, and oxide zones of 33.1%, 40.48% and 59.5%, respectively. The flotation method was applied under different conditions for all zones and the results were evaluated in terms of gold recovery and grade. The highest gold recoveries in the sulfide and transition zones have been achieved using Aero 8045 and PAX collectors, however the synergetic effect of the collectors (PAX-strong and Aero 407-selective) has been found to be useful. The flotation concentrate was also roasted and leached, but the Au recoveries achieved were not as high as those achieved by flotation. The blending potential of the zones was evaluated, and it was concluded that sulfide and transition zones could be processed together by flotation.

Keywords: refractory gold, flotation, recovery/grade, mineralogy, blending

## 1. Introduction

Gold can be found in nature in native and free form, but it can also be associated with other minerals or in the form of inclusions. These different forms of occurrence lead to the need for different processing methods. Determining the correct enrichment method requires mineralogical information describing gold formation, the minerals it is associated with and the degree of liberation. Gold ores are simply classified into three main groups such as free milling, complex, and refractory gold ores. Gold that is easily liberated by traditional milling methods when it is associated to another mineral is called "free milling gold ores" (Zhou et al., 2004). Ores containing minerals that cause reagent consumption or losses of valuable minerals during the enrichment process are called "complex gold ores" (Vaughan, 2004). The definition of refractory gold includes situations where the ore formations exhibit a resistance to conventional cyanide leaching even fine grinding is applied (Fernandez et al., 2000). Refractory gold refers to ore formations that exhibit a low response to standard cyanide leaching (<80%) (La Brooy et al., 1994) such as:

- The presence of ions that consume the oxygen necessary for dissolution to occur in cyanide leaching (Komnitsas and Pooley, 1989),
- The presence of compounds that are difficult to dissolve in cyanide solution, resulting in low gold recovery (Fernandez et al., 2000),
- Gold is present as sub-microscopic (solid solution, encapsulated in silica or colloidal) inclusions in the structure of other minerals and hence cannot reach the cyanide solution (La Brooy et al., 1994; Komnitsas and Pooley, 1989; Chen et al., 2002; Zaghloul, 2020),

- The presence of some sulfide minerals that form cyanicides and cause cyanide consumption (Komnitsas and Pooley, 1989),
- The presence of carbonaceous minerals leads to preg-robbing (Afenya, 1991),
- The presence of clay absorbing gold cyanides (Jha, 1987; Berezowsky and Weir, 1989).

According to these definitions in the literature, refractoriness exists when one or more of these conditions are present in an ore. In cases where fine gold grains are found as inclusions in the crystal structure of other sulfide or oxide minerals, the first solution is fine grinding. High recoveries can only be achieved by fine grinding if the gold occurs in the physical form of inclusions. However, if the gold grains are inclusions in sub-microscopic shapes, the refractoriness cannot be eliminated by fine grinding. Some pre-treatment- processes such as physical, chemical, biological, and thermal may be required for such gold ores (Spickelmier, 1993).

Gravity concentration, flotation, and conventional cyanide leaching are the well-known main methods for gold enrichment. Flotation is particularly preferred in refractory gold deposits where gold is associated with sulfide minerals or in areas where cyanide cannot be used due to its adverse effects. As a pre-enrichment product, the flotation concentrate is then subjected to another pre-treatment stage such as roasting, bacterial leaching or pressure oxidation to make it suitable for cyanide leaching. Applying these expensive pre-treatments to only the flotation concentrate products rather than the whole ore has a positive impact on operating costs (Bulatovic and Wyslouzil, 2000). In addition, flotation prior to cyanide leaching helps to remove other minerals that can cause cyanide consumption from the system, providing both capacity relief and reduced reagent consumption (Adams, 2005). There is still a lack of understanding of the flotation behavior of sulphide minerals containing free gold and refractory Au, despite a great deal of ongoing research in this area. While many studies have focused on the flotation of free gold, interactions with other gold-bearing minerals have not been sufficiently explored. Teague et al. (1999) showed in their study that the flotation of refractory gold is mainly influenced by the chemical conditions of the pulp, whereas the flotation of free gold is influenced by physical constraints such as grain shape, size and froth stability and is therefore directly proportional to water and gangue recovery.

The floatability of gold minerals and/or other gold-bearing minerals depends on many parameters such as the size and shape of free gold grains (Teague et al., 1999; Bulatovic, 1997), the Ag content of the native gold, the composition of the gold-bearing mineral (O'Connor and Dunne, 1991), the type and dosage of reagents used, the loading capacity of air bubbles, the Eh and pH of the pulp (Zaghloul, 2020). Free gold floats generally at natural pHs with a small amount of collector and dixanthogen form (Dunne, 2005; Miller et al., 1986). Some studies have shown that the potential values at which gold begins to float are close to the dixanthogen formation potential (Woods et al., 1994). As the chain length of the thiol collectors increases, the contact angle of the mineral with the froth increases, thereby increasing the hydrophobicity of the mineral surface. Therefore, long chain xanthates are preferred for free gold flotation (Dunne, 2005). At the same time, long chain collectors form dixanthogen at low potentials (Gardner and Woods, 1974). Most flotation plants now use the synergistic effect of collectors rather than a single collector type to achieve better results in terms of grade and recovery (Bradshaw and O'Connor, 1994). For example, dithiophosphates are preferred as secondary collectors along with xanthates to increase flotation efficiency because they are highly selective, especially for sulfide minerals (Dunne, 2005; Nagaraj, 1997; Allan and Woodcock, 2001). It was reported that when PAX was compared to dithiophosphates rather than used alone, gold recoveries could be improved from 70% to 82-88% depending on the PAX ratio for the same collector dosage (Bulatovic, 1997). Mercaptobenzothiazoles are important thiol-type collectors for the flotation of gold and gold-bearing minerals (Finkelstein and Poling, 1977) and are preferred for the flotation of gold and gold-bearing pyrite in acidic media (O'Connor and Dunne, 1991). These collectors have a fine crystalline structure and are therefore insoluble in water. However, they are readily soluble in alkaline solutions (Bulatovic, 2007).

The flotation of gold in free or refractory form, associated with sulfide minerals such as pyrite, pyrrhotite and arsenopyrite, varies depending on many parameters such as the addition of copper sulfate (CuSO<sub>4</sub>), pre-aeration, galvanic interaction, synergistic effects of collectors used. For example, it is reported that gold recoveries varied in flotation tests using sodium isobutyl xanthate (SIPX) collector at different pHs and CuSO<sub>4</sub> dosages of sulfide refractory gold ore from a gold mine in Ghana, West

Africa (Owusu et al., 2020). Flotation kinetics were observed to be faster in acidic media without copper activation, but adsorption decreased in alkaline media (pH10-10.5) due to competition between OHand SIPX. Oxidation products (arsenic oxides and ferric hydroxide) are hydrophilic in nature and act as a barrier to collector interaction with sulfide minerals present in the ore (Valsivieso, 2006). The effect of copper activation on pH and SIPX adsorption was investigated, and it was concluded that the maximum adsorption occurred in the natural pH range of 8-8.5 and resulted in maximum gold recovery of 91%. Total gold recovery was approximately 7% higher when CuSO<sub>4</sub> was added after the xanthate than when it was added before the xanthate. This is because up to 10% more free gold is recovered in the concentrates due to increased entrainment and true floatation of the free gold. A study by Teague et al. (1999) reported that for Stawell Central ore containing both free and refractory gold, the order of addition of CuSO4 before or after the collector changed the Au recovery. The reason for this is that the strong hydrophobic Cu-X compounds formed by CuSO<sub>4</sub> activation, and the sulfide minerals adhere to the air bubbles in significant quantities, reducing the chance of free gold adhesion and reducing the recovery by entrainment. The use of copper sulfate is claimed to affect pyrite flotation, depending on the dosage, in some cases improving gold recovery (Allison et al., 1982), and sometimes, as a result of the relationship between Cu ion and contact angle, air bubbles tend to coalesce and collapse (O'Connor et al., 1988). It has been reported that sulphidization with metal ions such as Cu/Pb results in the formation of new copper-lead sulfide on the mineral surface, which improves the floatability of the metal oxide mineral, promotes xanthate adsorption and thus increases surface hydrophobicity (Feng et al., 2024).

Selective and bulk flotation options have also been investigated in cases where gold is associated with other minerals. In a study investigating flotation, pre-oxidation, and cyanidation methods for low-grade refractory gold ore (Soltani et al., 2014), the application of bulk flotation resulted in an Au recovery of 90.6%, while the selective flotation achieved only 24% of recovery. It has also been reported that using bulk flotation as a pre-treatment resulted in concentrate with less penalty elements such as As and Sb for downstream processes (Badri and Zamankhan, 2013). In a recent study (Lee et al., 2021), refractory gold ore containing both carbonaceous matter and sulfide from the Nevada Goldstrike Mine was examined, and flotation of carbonaceous matter was investigated to improve Au recovery in thiosulphate leaching, which was inadequate after alkaline pressure oxidation.

In this study, the mineralogical characterization and metallurgical deportment of different zones of a refractory gold deposit located between the North Anatolian and East Anatolian Fault Lines, were performed. The characterization studies were designed to determine the occurrence, association and refractoriness of the gold and based on this information; the appropriate processing method was selected. The next step was to evaluate the potential of processing different zones together in terms of mineralogy and refractoriness using a single method.

#### 2. Materials and methods

Representative core samples were collected from different locations to provide an overall characterization of the deposit. The modal mineralogical compositions/associations were determined at Amtel laboratories (Canada) using QemSCAN-SEM/EDX (Quantitative Evaluation of Minerals by Scanning Electron Microscopy). As a result of this preliminary study, which examined the gold deportment in detail, the ore deposit was classified into three main types, oxide, transition, and sulfide, based on structural characteristics.

Following the identification of the zones, new samples were collected from various meters of selected drill logs representing each zone and they were prepared for detailed mineralogical characterization, chemical analyses, and metallurgical testing. Within the scope of chemical analysis, all base metals were determined by ICP (Inductively Coupled Plasma Emission Spectrometry-Agilent 5800 ICP-OES) method while for gold values, fire assay method was used. The surface oxidation of the samples representing the zones was determined by the EDTA (ethylene diamine tetra acetic acid) method, and the solid and liquid phases after the EDTA test were analyzed by Atomic Absorption Spectrometry (AAS- PerkinElmer AAS PinAAcle 900F). Detailed mineralogical characterization analysis was carried out by preparing -106+53µm and -53+20µm fractions of representative samples from each zone to be used in enrichment tests. Modal mineralogy, XRD (X-ray Diffraction), SEM

(Scanning Electron Microscope), and EDS (Energy Dispersive Spectrometry) were performed by MLA (Mineral Liberation Analyzer) method, using FEI MLA 650.

The first phase of the studies involved bottle roll testing to prove the refractoriness of the deposit, which was defined as refractory by mineralogical tests, and to investigate the susceptibility of the ore deposit to conventional cyanide leaching. Forty-eight drill core samples representing the sulfide, transition and oxide zones were crushed and sieved using jaw and roller crushers to a particle size of  $p_{80}$ : 1.7 mm and prepared as 500 g for bottle-roll tests. The samples were then placed in 2.5-liter amber glass bottles and rotated for 120 hours under atmospheric conditions with sodium cyanide (NaCN) at a concentration of 1g/L and 750 mL of distilled water. Oxygen was supplied by atmospheric air throughout the test and no external air was added (Fig. 1). The pH of the pulp (pH>10.5 - 11.0) and the amount of dissolved oxygen in the solution (>4 mg/L), which influence the leaching kinetics and the interaction with cyanide, were measured periodically throughout the test and were always kept within ideal limits.



Fig. 1. Bottle-roll test set-up

Flotation was the preferred method for enrichment based on the information that gold is associated with pyrite minerals in sulfide and transition zones. Prior to the flotation tests, the grinding was carried out in a rod mill using 1 kg of ore at a solid density of 60% (w/w). Flotation tests were carried out using a 2.5-liter Denver type flotation machine at a speed of 1500 rpm, an air flow of 3.5 liters per minute and a solids density of approximately 30% (w/w). In the grinding stage, 2 kg/t sodium silicate (Na<sub>2</sub>SiO<sub>3</sub>) was used as dispersant and MIBC (methyl isobutyl carbinol) was preferred as frother. Preliminary tests using a strong collector, potassium amylxanthate (PAX), were conducted prior to flotation based on information that gold was associated with pyrite. In these tests, the effect of pH was also analyzed. Considering the liberation data, grinding calibration was performed for each sample of the zones and the samples were ground to  $p_{80}$ : 50 µm,  $p_{80}$ : 42 µm and  $p_{80}$ : 43 µm for the sulfide, transition, and the oxide zones, respectively. The collectors used for the flotation tests were selected from those commonly used for iron sulfide, FeOx and Au (Aravjo, 2005; Bulatovic, 2007). For anionic collector, petroleum-based sulfonates were preferred (Day, 2002 and Nakhaei, 2018). The following collector types were scanned for the zones:

- PAX (potassium amyl xanthate)
- Aero 407 promoter (mercaptobenzothiazole and dithiophosphate formulation)
- XD-702 promoter (formulated dithiocarbamate)
- Aero 8045 (Dithiophosphate formulation)
- Aero Maxgold 900 (modified dithiocarbamate)
- Aerofloat MX-505 (dithiophosphate)
- Aero 825 (petroleum sulfonate)

The next step was to use some of the collectors together to improve Au recovery and explore their synergy. Once the most appropriate collectors were identified, the zones were blended according to their reserve ratios and flotation tests were carried out. Blend1 was prepared by mixing the sulfide and transition zone while Blend2 was the blend of all three zones.

Roasting and leaching methods were conducted on the flotation concentrate of sulfide zone. Roasting was applied at 600-650°C for 1 hour using Cress Electrical Furnace. In the leaching process, NaCN solution at a concentration of 10000 ppm was treated with a 20% solids pulp sample for 48 hours at pH 11-11.7. During the leaching period, the amount of Au leached and the total consumption of NaCN were measured at the beginning of the experiment and at the end of the 2<sup>nd</sup>, 5<sup>th</sup>, 24<sup>th</sup> and 48<sup>th</sup> hours, and the time-dependent Au extraction recovery was calculated.

#### 3. Results and discussion

#### 3.1. Ore characterization

The drill core samples selected for general characterization of the ore deposit have been classified according to their mineral content as sulfide (KT2, KT3 and KT6), transition (KT1, KT4 and KT7) and oxide (KT5 and KT8) ores. According to the modal mineralogy data given in Table 1, quartz and K-feldspar are the major gangue minerals in all three zones. While pyrite is the dominant sulfide mineral in the sulfide zone samples, goethite mineral is prominent in the oxide zone. The fact that the amounts of both pyrite and goethite are close in the transition zone samples shows that the mineralogical analysis and oxidation classification are not in conflict.

		Codes of drill-core samples										
Mineral	KT-1	KT-2	KT-3	KT-4	KT-5	KT-6	KT-7	KT-8				
Quartz	35.0	39.4	42.0	62.0	36.0	38.3	30.6	34.0				
K-Feldspar	30.8	29.7	18.4	5.5	26.4	30.3	25.0	19.7				
Na-Feldspar	3.9	1.7	0.9	0.4	1.5	1.3	9.8	3.4				
Illite	13.2	11.5	14.4	10.9	14.7	10.9	17.9	19.9				
Biotite	2.7	1.2	1.0	2.1	2.9	1.0	2.2	4.4				
Kaolinite	7.6	3.7	9.3	4.9	13.8	12.4	7.7	8.0				
Chlorite	0.0	0.0	0.0	0.0	0.0	0.0	1.2	3.5				
Rutile	0.2	0.2	0.2	0.1	0.2	0.1	0.2	0.2				
Barite	0.2	0.1	0.1	0.2	0.2	0.1	0.1	0.2				
Goethite	3.1	1.2	0.0	4.5	3.5	0.1	3.2	5.6				
Pyrite	2.7	11.0	12.8	9.1	0.3	2.0	1.0	0.0				
Arsenopyrite	0.6	0.0	0.0	0.0	0.1	0.1	0.2	0.0				
Galena	0.0	0.2	0.1	0.1	0.0	0.0	0.0	0.0				
Sphalerite	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0				
Augite	0.0	0.0	0.0	0.0	0.0	3.4	0.9	0.0				
Total	100	100	100	100	100	100	100	100				

Table 1. The modal mineralogy of the samples representing the ore deposit

It has been observed that visible gold particles are both free and associated with sulfides and iron oxides (Fig. 2). Sub-microscopic gold is also found as a solid solution with pyrite and arsenopyrite, and in colloidal micro-inclusions within FeOx (Fig. 3).

After classification, the head assays of all three zones were determined (Table 2). Overall, the Au content of all zones is quite low, however the Au grade of the sulfide zone is slightly higher than the other zones and the Au grades of the transition and oxide zones are relatively close.

As a result of the EDTA test, the Es\_Fe value in the sulfide zone was calculated as 0.80 mg/g, 0.84 mg/g in the transition zone and 0.60 mg/g in the oxidized zone. These values are an indication that Fe minerals are not exposed to surface oxidation.

According to modal mineralogy (Table 3), quartz, feldspar and pyrite minerals account for approximately 87% of whole sulfide zone both in coarse and fine fractions. Quartz, feldspar, Fe-oxides, muscovite, and pyrite are the major minerals in the transition zone. In the oxidized zone, quartz, feldspar, and Fe-oxides are dominant. According to the results of chemical analyses, the native gold content in the zones is 1 ppm or less. The number of gold grains detected in the MLA analysis is given in Table 4. The trace amounts of these gold grains indicate the refractoriness of these samples.

According to the resource estimation report, the ore deposit consists of 83% sulfide zone, 10% oxide zone and 7% transition zone. Mineralogical characterization studies showed that gold grains were 100% of association with pyrite particularly in sulfide and transition zones. A typical BSE (back scattered electron) image and MLA mapping for the transition zone is depicted in Fig. 4.



Fig. 2. The liberation of native gold and its association with other minerals

#### Sub-microscopic Gold (Pyrite)



# Sub-microscopic Gold (FeOx)

Fig. 3. Association of sub-microscopic gold with other minerals

Zono	Au	Ag	As	Cu	Pb	Zn	Sb	Ni	Fe	S
Zone	(ppm)	(%)	(%)							
Sulfide	1.13	10.4	2894	235	1430	911	343	24	5.73	5.77
Transition	0.71	3.5	2329	61	202	91	49	12	3.71	1.79
Oxide	0.76	1.7	3584	66	347	208	1534	15	4.94	0.22

	Distribution (%)						
	Sulfide Zone		Transitio	on Zone	Oxide Zone		
	-106+53 μm	-53+20 μm	-106+53 μm	-53+20 μm	-106+53 μm	-53+20 μm	
Quartz	43.15	36.33	51.25	47.64	48.80	46.56	
K-feldspar	25.56	23.41	21.71	24.79	29.75	32.41	
Albite	2.33	2.67	2.24	0.00	1.53	1.46	
Pyrite	19.26	27.54	7.26	9.67	0.55	1.25	
Arsenopyrite	0.42	0.99	0.68	1.12	0.02	0.07	
Kaolinite	0.59	0.56	1.28	1.28	1.43	1.1	
Fe-oxide	0.37	0.65	5.67	4.03	10.35	10.57	
Muscovite	5.88	4.69	6.84	5.40	3.74	3.02	
Biotite	0.19	0.34	1.85	2.18	1.01	0.92	
Rutile	0.07	0.13	0.06	0.13	0.14	0.25	
Barite	0.03	0.18	0.20	0.21	0.14	0.22	
Dolomite	1.20	1.24	0.01	0.01	0.03	0.01	
Plagioclase	0.00	0.00	0.55	2.84	0.12	0.00	
Sb_Fe Oxide	0.00	0.00	0.00	0.00	0.90	1.46	
Apatite	0.09	0.16	0.11	0.25	0.01	0.01	
Jarosite	0.00	0.00	0.06	0.00	0.22	0.26	
Sphalerite	0.20	0.25	0.00	0.00	0.00	0.00	
Chlorite	0.00	0.00	0.00	0.18	0.84	0.01	
Others	0.66	0.86	0.23	0.27	0.42	0.42	
Total	100.00	100.00	100.00	100.00	100.00	100.00	

Table 3. The modal mineralogy of the zone
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Table 4. Number of Au grains detected in all zones

Zones	Size (µm)	# of Au grains
T	-106+53	3
Transition	-53+20	1
0.11	-106+53	0
Oxide	-53+20	0
C 10:1	-106+53	0
Sulfide	-53+20	2



Fig. 4. The association of pyrite with gold in the transition zone

As pyrite was accepted as the target mineral, its liberation status was examined in detail. The degree of pyrite liberation was recorded as 89.79%, 84.12% and 77.92% for the sulfide, transition, and oxide zones respectively in the -106+53  $\mu$ m fraction, while these values were 93.20%, 91.33% and 94.28% for the -53+20  $\mu$ m fraction in the order of the zones indicated. Even in the fine size fraction of the sulfide (Fig. 5a) and transition zones (Fig. 5b), 100% of the gold was observed to be in the form of binary particles.



Fig. 5. The liberation of sulfide minerals and gold in -53+20μm fraction of sulfide zone (a) and -106+53μm fraction in transition zone (b)

Although gold was detected in the oxidized zone as a result of chemical analysis, no gold grains were found in MLA analysis. However, preliminary analyses conducted to characterize the deposit have reported that gold is present in the oxide zone in sub-microscopic form and generally with Fe-Oxides (Fig. 3). Accordingly, Fe-Oxides detected in the MLA analysis were considered to likely contain gold and therefore their locking status was also investigated. Fe-Oxides were found to have less liberation compared to pyrite (62% liberation in coarse size and only 70% in fine size) and exhibited a more complex mineralogy in the form of both binary and multiple locked grains with minerals such as quartz, Sb-oxide, K-feldspar. The following tables summarize the liberation status of gold-related minerals such as pyrite (Table 5) and FeOx (Table 6), as well as their binary and multiple associations with other minerals.

Examining the liberation status of the gold grains, which could be counted in a few numbers in the MLA analysis, it was concluded that gold was locked only with pyrite mineral in both the sulfide and transition zones and only in the 0%<x<15% liberation class of particle area. It is concluded that pyrite in particular can be recovered by sulfide mineral flotation and that maximizing pyrite recovery would be important in terms of gold recovery.

		Binary associated (%)							Male	
Zones	μm	Free	Quartz	Galena	K- Feldspar	As- pyrite	Muscovite	Others	(%)	Tot.
Cultida	-106+53	89.79	4.67	0.15	1.89	0.56	0.82	0.91	1.21	100
Suinde	-53+20	93.20	3.02	0.30	0.71	0.47	0.36	1.31	0.63	100
		Free	Quartz	Fe-Ox	K- Feldspar	As- pyrite	Au	Others		
Turneitien	-106+53	84.12	6.72	1.75	0.95	0.36	0.05	3.38	2.67	100
Transition	-53+20	91.33	3.26	1.15	0.88	0.56	0.00	1.68	1.14	100
		Free	Quartz	Fe-Ox	K- Feldspar	As- pyrite	Jarosite	Others		
0.11	-106+53	77.92	6.30	8.60	2.47	0.74	0.00	0.34	3.63	100
Oxide	-53+20	94.28	0.49	0.96	0.09	0.65	3.01	0.48	0.04	100

Table 5. Association of pyrite in all zones

Table 6. Association of Fe-Ox in oxide zone

Error		Binary associated (%)							Tat	
	μm	Free	Quartz	Sb_Fe Ox	K-Feldspar	Muscovite	Kaolinite	Others	(%)	Tot.
Ovida	-106+53	61,98	10,31	2,15	6,68	1,84	1,52	4,15	11,37	100
Oxide	-53+20	70,44	5,51	5,04	5,70	1,11	1,16	3,00	8,05	100

#### 3.2. Enrichment tests

#### 3.2.1. Bottle-roll tests

The bottle-roll test, carried out on forty-eight drill core samples representative of the ore deposit, was designed to determine the refractory nature of the gold content in the zones. The samples were taken from different depths and locations of the deposit (Table 7). After approximately three months of bottle-roll testing, the leaching efficiency of the three zones was found to be highly variable and this variability was not correlated with depth. Bottle roll test results for samples taken from various depths and locations in the oxide zone indicate that Au leach recoveries and grades ranged from 9-79.6% and 0.24-0.87 ppm, respectively. For the transition zone, Au leach recoveries ranged from 10.6-74% and Au grades from 0.04-1.11 ppm, while for the sulfide zone these values ranged from 8.6-72.6% and 0.19-1.30 ppm, respectively. It is known from mineralogical analysis that there were no carbonaceous structures in the ore that would cause cyanicides or 'preg-robbing'. Therefore, given the low cyanide consumption and low/medium gold leach recoveries of the samples, this ore deposit has been classified as "refractory".

Table 7. Results of bottle-roll tests							
Zone	Drill cores (meter)	# of samples	Average Au grade (ppm)	Average Au leach recovery (%)			
Oxide	1.90-69.50	9	0.60	59.50			
Transition	44.20-137.80	7	0.67	40.48			
Sulfide	55.60-288.50	32	1.06	33.31			

#### 3.2.2. Flotation tests

To determine the optimum flotation condition, preliminary tests were performed to analyze the effect of pH. Flotation was conducted at both acidic (pH: 6) and neutral (pH: 8.5-9) pH values to examine its effect, particularly on gold recovery. It has been reported that xanthates are more unstable at acidic pH (Day, 2002) and neutral values such as 8-8.5 give more favorable results, particularly in terms of gold recovery, rather than acidic and alkaline pH (Owusu et al., 2020; Goktepe, 2002). A similar result was obtained in this study that pH 8.5-9 range gave the most proper results (Table 8).

Table 8. Effects of pH					
Condition	Au recovery, %				
Acidic pH	36.6				
Neutral pH	97.0				

It is known that in acidic solution xanthate is protonated to form xanthic acid, which is unstable and rapidly decomposes into carbon disulfide and alcohol at pH 5.5 (Owusu et al., 2020). The most general reaction mechanism is given below (Eq1):

Dixanthogen is known to be the major xanthate species responsible for pyrite flotation. At high pH (pH<9-10), adsorption is reduced because hydroxyl ions are in competition with xanthate for adsorption, the degree of competition being highly sensitive to the surface composition of the mineral. Some researchers have found that sulfidic refractory gold ore floats much better at its natural pH (8-8.5) than in acidic or basic solutions (Owusu et al., 2020; Valsivieso, 2006). Sun and Forsling (1997) also observed an increase in xanthate degradation at pH < 7. This suggests that xanthate degrades more rapidly in acidic solution. The maximum half-life of xanthate occurred at pH 7-8, whereas degradation was found to be much faster at pH 9-10. These results indicate that even slight changes in the pH of the solution can cause differences in the degradation rate of xanthate. It is believed that such low Au recoveries in acidic solution are due not only to the pH conditions but also to the genesis characteristics of pyrite.

#### 3.2.2.1. Sulfide zone

As a result of preliminary testing on collector dosage and staged addition, it was determined that better results in terms of gold recovery could be achieved by staged addition of the collector at a total dosage of 250 g/t for the sulfide zone. In addition to PAX, a strong collector known to give efficient results in gold and pyrite flotation, kinetic tests were carried out with five different collectors (Aravjo, 2005; Bulatovic, 2007). Fig. 6a shows that the highest Au recovery (98.6%) was achieved with MX-505, while the lowest Au recovery (60%) was observed with XD-702 collector. It was noted that the flotation behavior of PAX, Aero 8045, and Aero 407 were similar, particularly in the initial minutes (Fig 6b). However, in the cumulative concentrate, Aero 8045 and Aero 407 were more selective than other types of collectors. The higher Au recovery (Fig. 6d) values with the other collectors was achieved with lower mass pull (Fig. 6c) and pyrite recovery (Fig. 6d) values with the Aero 8045 and Aero 407 collectors, indicating that these collectors were more selective. It is possible to explain why longer chain xanthates such as PAX provide higher Au recoveries for gold flotation based on the knowledge that longer chain xanthates are more readily oxidized and produce dixanthogens at low potentials (Gardner and Woods, 1974), and that an increase in thiol chain length increases the maximum contact angle and hence the hydrophobicity of surface species.



Fig. 6. Au recovery & grade (a), flotation time (b), mass pull (c) and pyrite recovery (d) relationship with different collectors for the sulfide zone

Following the single collector tests, the potential synergistic effects of the combined use of collectors on Au recovery were investigated. In terms of collector preference, one collector was chosen for its low cost and the high performance, while the second collector was chosen for its selectivity. Hence, in the collector mixtures, Aero 407 and Maxgold 900 collectors were added to PAX for further testing in 1:1 ratio. The results show that the PAX+Aero 407 mixture has a recovery of 94% Au, while PAX+Maxgold 900 mixture has a recovery of 88.4% (Fig. 7a). In addition, when the synergistic effect of the collectors was compared with the tests using Aero 407 and PAX separately, it was found that the highest grade of Au was obtained using the combination of these collectors. The comparison of pyrite and Au recoveries for the collector mixtures is given in Fig. 7b. It is stated that the combination that is more favorable to pyrite was PAX+Aero 407. The higher Au recoveries from the PAX and Aero 407 mix compared to the PAX and Maxgold mix can be attributed to the preferential success of Aero 407 in the flotation of auriferous pyrite grains. In this refractory ore type, which has similar mineralogy in both the sulfide and transition zones, the contribution of Aero 407 stands out, particularly because gold is associated with pyrite at fine grain sizes.



In all flotation tests conducted on the sulfide zone, Au grades in the tailings ranged from 0.02 ppm to 0.16 ppm and varied depending on the type of collector and mix used.

Fig. 7. Au recovery & grade (a) and pyrite recovery (b) relationship with combination of collectors for the sulfide zone

#### 3.2.2.2. Transition zone

Mineralogical and chemical analyses indicate that the transition zone has lower Au content, less liberation of Au-bearing pyrite and more locked grains compared to the sulfide zone. Based on these data and due to the sub-microscopic form of gold, the grain size of the sample was ground finer with a  $p_{80}$  value of ~42 µm. As a result of this test, where PAX was staged added in 250 g/t dosage, the cumulative Au recovery in the concentrate was recorded as 77.4% despite finer grinding. Whether the lower recovery and grade values obtained despite finer grain size were related to the collector dosage was evaluated as a second test condition by gradually increasing the PAX dosage to 300 g/t. It was observed that increasing the PAX dosage improved the flotation kinetics from the first few minutes of flotation and increased the Au recovery to 86.1%. With the increase in PAX dosage, Au grade increased from 3.3 ppm to 5.2 ppm in the cumulative concentrate. Therefore, in subsequent flotation testing of the transition zone, which is less pyritic than the sulphide zone, it was deemed appropriate to use the collector at a dosage of 300 g/t.

Kinetic tests for the transition zone were conducted using PAX, Aero 8045, and Aero 407 collectors, which gave the highest recoveries for the sulfide zone. Au recoveries of 86.1%, 86.7% and 75.3% were achieved for PAX, Aero 8045, and Aero 407, respectively. It was observed that PAX and Aero 8045 collectors gave similar results (Fig. 8a). Although Aero 8045 and PAX have similar recoveries during flotation time (Fig. 8b), it is observed that Aero 8045 collects Au-bearing pyrite particles into the concentrate better than PAX (Fig. 8c). Fig. 8d shows the relationship between Au recovery and pyrite recovery for these three collectors.

As the PAX+Aero 407 combination gave the most favorable results in the collector mixtures tested for the sulfide zone, flotation tests were carried out using the same approach for the transition zone sample. Au recovery and grade were noted as 80.7% and 10.4 ppm respectively with combined use of PAX+Aero 407 in a ratio of 1:1. In terms of Au grade, concentrate was obtained at a better grade than when these two collectors were used separately. It was observed that the selectivity effect of Aero 407 was reflected very well in the grade, but did not provide the desired efficiency in the recovery (Fig. 9).

In all flotation tests conducted on the transition zone, Au grades in the tailings ranged from 0.1 ppm to 0.2 ppm and varied depending on the type of collector and mix used.

#### 3.2.2.3. Oxide zone

Mineralogical and chemical analyses indicated that S and Au contents were low in the oxidized zone and sulfide minerals existed in trace amounts. The mineralogical evaluation, which was primarily performed to characterize the deposit, reported low levels of Au grains mostly associated with FeOx minerals. However, a test was conducted to get an idea of how the oxide zone would respond to sulfide mineral flotation when mixed with the sulfide and transition zones. The test, in which PAX was added

in stages at 250 g/t, resulted in a cumulative concentrate with a recovery of 37.7% Au and a grade of 1.6 ppm Au. In the next stage, based on the data that gold is associated with FeOx minerals, the aim was to float these minerals. Aero 825, a petroleum-based sulfonate type collector commonly used in FeOx mineral flotation, was tested as in 500 g/t dosage and at pH 5-5.5. As a result of several repeated flotation tests, no successful results were achieved in terms of Au recovery and grade, with the best results being 27% and 0.9 ppm, respectively. However, the higher recovery and grade obtained with PAX suggests that gold may not only be present with FeOx minerals. It may be recommended to further characterize the sub-microscopic gold in this zone by Electron Microprobe Analysis or Laser Ablation ICP-MS methods (Chingwaru et al. 2024)



Fig. 8. Au recovery & grade (a), flotation time (b), mass pull (c) and pyrite recovery (d) relationship with different collectors for the transition zone



Fig. 9. Au recovery & grade relationship for the collector mixture in the transition zone

### 3.2.3. Roasting and leaching tests

Refractory gold concentrates may need oxidative pre-treatments, such as roasting, bacterial or pressure leaching in order to upgrade recoveries and achieve economic feasibility (De Michelis, 2013; Adams et al, 2011). To this end, roasting, one of the pre-treatments to remove refractoriness, was applied to the

flotation concentrate, followed by leaching to improve Au recovery from the pre-treated flotation concentrate. In this regard, the flotation concentrate of the sulfide zone, which is richer in terms of both reserve and Au content, was used in the tests. To enrich refractory gold by conventional leaching, gold grains in the form of inclusions must first be released from the lattice structure of the mineral. This allows the gold grains to come into contact with cyanide and dissolution takes place (La Brooy et al., 1994). After roasting at 600-650°C for 1 hour, the solution having 10000 ppm NaCN was leached with flotation concentrate for 48 hours and gold extraction recoveries were calculated by sampling at the initial, 2<sup>nd</sup>,5<sup>th</sup>, 24<sup>th</sup> and 48<sup>th</sup> hour. The leaching process was also applied directly to the flotation concentrate without roasting. Fig. 10a shows that the leaching process was substantially completed in 5 hours for both conditions and the Au leach recovery after roasting reached approximately 90%, while the Au recovery from direct leaching without roasting remained at ~81%. Although leaching recovery followed roasting resulted in ~10% improvement rather than direct leaching, they both could not reach the recoveries achieved by flotation alone. The increase in NaCN consumption in the leaching process also has a negative impact (Fig. 10b).



Fig. 10. Time-dependent Au extraction recovery (a) and cumulative NaCN consumption (b) for roasting+leaching and direct leaching options

It can be said that the 81% recovery obtained by direct leaching is consistent with the bottle roll test results. The maximum leach value obtained in the sulfide zone from the bottle roll test was 72.6%. The highest Au grade of the bottle roll test samples was 1.3 ppm with a grain size of  $p_{80}$ :1.7 mm as stated in the Materials and Methods section. However, it is clear from the flotation tests that the Au content of the concentrate is higher in the leach process applied to the flotation concentrate belonging to the sulfide zone and it should be noted that the  $p_{80}$  value is much finer (50 µm). It is well known from the literature that as the particle size decreases, extraction efficiency and leaching kinetics improve (Adams, 2005; Celep et al., 2010). However, this effect has a limited impact on this ore deposit because gold is present as fine-grained native gold and in refractory form. In addition, the complex nature of the ore body results in variability in the degree of refractoriness as it is confirmed by the wide range of leach recovery values of ~8-80% obtained from the bottle-roll tests. These results showed that the mineralogical structure of the ore makes a significant contribution to refractoriness and that even roasting followed by leaching did not recover the desired amount of gold into solution, which is highly associated with the sulfide mineral.

#### 3.2.4. Blend possibility of the zones

Among the flotation, roasting and leaching methods applied, it was concluded that flotation would be the more effective processing method in terms of Au recovery, economic and environmental factors. Accordingly, studies were conducted to determine the flotation behavior of these three zones when processed together. For this purpose, two different blends were prepared from the zones defined as sulfide, transition, and oxide zones by blending them in the proportions of the reserve amount indicated in the resource estimation report of the ore deposit. As the sulfide and transition zones are mineralogically and chemically similar, sample Blend1 was prepared by blending 92.2% from the

sulfide zone and 7.78% from the transition zone. Blend2 was prepared by adding 10% material from the oxide zone to investigate the possibility of blending this zone into Blend1 over time in the plant. As the PAX-Aero 407 collector mixture had shown positive results in previous tests, particularly in terms of selectivity and recovery, it was tested at a ratio of 1:1 ratio for both blends. Fig. 11 clearly shows that the mixing of sulfide and transition zones, which have similar characteristics, is not a problem in terms of Au recovery and grade. However, with the addition of the oxide zone to this mixture, the ore behavior deteriorates, especially in favor of grade. It should be considered that the oxide zone should not be processed with the other zones until further detailed characterization studies are carried out in terms of Au content and mineral association.



Fig. 11. Au recovery & grade relationship for the blend samples

#### 4. Conclusions

This study has demonstrated that mineralogical characterization is a useful tool in assessing the effects of gold ore refractoriness on the rougher flotation stage. Accordingly, the following findings are derived:

- The ore deposit has been classified into three distinct zones as sulfide, transition, and oxide according to the mineral classes/quantities present, with Au grades of 1.13 ppm, 0.71 ppm and 0.76 ppm, respectively.
- The main sulfide and Au-bearing mineral in the sulfide and transition zones was determined to be pyrite and the grain size of native gold was <10 μm from MLA BSE images. In the oxide zone, gold was reported to be sub-microscopic in size and associated with FeOx minerals in the preliminary characterization study, but no gold-bearing grains were detected in the MLA analysis.
- The average Au recoveries of the sulfide, transition and oxide zones obtained from the bottle-roll tests were calculated to be 33.1%, 40.48% and 59.5%, respectively. The low gold Au recoveries of all zones indicate that the ore deposit can be classified as refractory.
- It was found that the flotation behavior of PAX, Aero 8045 and Aero 407 in the sulfide zone was similar, especially in the first few minutes of flotation, but 97% recovery was achieved with PAX and Aero 8045 for the cumulative concentrate. The potential synergistic effects of using these collectors together on gold recovery were also investigated. The PAX+Aero 407 collector mixture resulted in a cumulative Au recovery of 94% and provided a more selective concentrate compared to the other collector mixtures.
- For the transition zone, PAX and Aero 8045 collectors gave similar results. However, the combination of PAX and Aero 407 collectors failed, while the selectivity effect of Aero 407 was evident in the grade, with Au recovery remaining at 80%.
- Unfortunately, flotation using the Aero 825 sulfonate type collector, based on the data that gold is associated with FeOx minerals at sub-microscopic size, was not successful. It is concluded that the flotation conditions should be optimized after the occurrence of gold in this zone has been determined by a more detailed mineralogical characterization study.

- Roasting followed by leaching was applied to the flotation concentrate of sulfide ore to remove refractoriness and improve Au recovery. However, the Au recoveries achieved by the roasting and leaching methods did not match those achieved by flotation alone. This result confirms that the mineralogy of the ore has a significant effect on refractoriness.
- The blending strategy for these three zones was also evaluated and successful results were achieved using a mixture of PAX and Aero 407 for the sulfide and transitional zones.
- The results show that in particular sulfide and transition zones can be processed together, bulk flotation method can be applied, and high recoveries of concentrate can be achieved with the Aero 8045 collector alone or with PAX + Aero 407 collector mixtures. However, the presence of gold in the ore deposit in a sub-microscopic form and at very low grade confirms the refractoriness of the ore deposit. Implementing a regrinding stage prior to obtaining the final concentrate can be considered. Based on the data in this study, it is concluded that the oxide zone should not be mixed with the other two zones given the amount of reserves. It is recommended that this zone be further investigated by both gravity and flotation methods. It is clear that the blending strategy is important for both mine planning and sustainability of resource utilization, particularly in a deposit with multiple zones.
- For the leaching process to be successful, it may be suggested to perform the leaching process after the ore has been ground to to a finer particle size to reduce the interlocking of gold within other minerals and to facilitate the penetration of solvent liquid. In this case, however, the cost of grinding should also be considered. To optimize all these methods, mineralogical analysis by EMPA or laser ablation, which can provide more detailed data on this zone, will certainly provide more useful information.

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#### References

ADAMS, M.D., 2005, Advances in Gold Ore Processing, Elsevier.

- ADAMS, M., LIDDELL, K., HOLOHAN, T., 2011, *Hydrometallurgical processing of Platreef flotation concentrate*, Miner. Eng., 24 (6), 545-550.
- AFENYA, P.M., 1991, Treatment of Carbonaceous Refractory Gold Ores, Miner. Eng., 4(7-11), 1043-1055.
- ALLAN, G.C., WOODCOCK, J.T., 2001, A review of the flotation of native gold and electrum, Miner. Eng., 14(9), 931–962.

ALLISON, S.A., DUNNE, R.C., De WAAL, S.A., 1982, *The flotation of gold and pyrite from South African gold-mine residues*, In: 14<sup>th</sup> International Mineral Processing Congress, Toronto, Canada, paper II-9.18.

ARAVJO, A.C., VIANA, P.R.M., PERES, A.E.C., 2005, Reagent in iron ores flotation, Miner. Eng., 18(2), 219-224.

- BADRI, R., ZAMANKHAN, P., 2013, Sulphidic refractory gold ore pre-treatment by selective and bulk flotation methods, Advanced Powder Technology 24(2), 512-519.
- BEREZOWSKY, M.G.S., WEIR, D.R., 1989, Factors affecting the selection of pressure oxidation for the pretreatment of refractory gold ores, Paper Presented at the E&MJ International Gold Expo and Conference, Reno, NV, Sept. 7-9.
- BULATOVIC, S.M., 1997, Flotation behavior of gold during processing of porphyry copper-gold ores and refractory gold bearing sulfides, Miner. Eng. 10(9), 895-908.
- BULATOVIC, S., WYSLOUZIL, D.M., 2000, Gold Recovery: Flotation, Lakefield Research, Ontario.
- BULATOVIC, S.M., 2007, Handbook of flotation reagents, Vol. 1, Elsevier.
- BRADSHAW, D.J., O'CONNOR, C.T., 1994, The flotation of pyrite using mixture of dithiocarbamates and other thiol collectors, Miner. Eng., 7(5-6), 681-690.
- CELEP, O., ALP, I., DEVECI, H., 2010, Improvement of Cyanidation of Antimonial Refractory Gold/Silver Ores by Ultrafine Grinding in a Stirred Mill, 12. International Mineral Processing Symposium, Cappadocia, Nevşehir, Oct. 6-8.
- CHEN, T.T., CABRI, L.J., DUTRIZAC, J.E., 2002, Characterizing gold in refractory sulfide gold ores and residues, JOM, 54(12), 20–22.

- CHINGWARU, S.J., TADIE, M., VON DER HEYDEN, B., 2024, Characterizing low-grade refractory gold ores using automated mineralogy coupled with LA ICP-MS, Miner. Eng., 210.
- DAY, A., 2002, Cytec Mining chemicals handbook, Revised Edition.
- DE MICHELIS, I., OLIVIERI, A., UBALDINI, S., FERELLA, F., BEOLCHINI, F., VEGLIÒ, F., 2013, *Roasting and chlorine leaching of gold-bearing refractory concentrate: Experimental and process analysis*, Int. J. of Mining Sci. and Tech., 23 (5), 709-715.
- DUNNE, R., 2005, Flotation of gold and gold-bearing ores, Developments in Mineral Processing, Vol. 15, Elsevier, Chapter 14.
- FENG, Q., ZHANG, Y., ZHANG, G., HAN, G., ZHAO, W., 2024, A novel sulfidization system for enhancing hemimorphite flotation through Cu/Pb binary metal ions, Int. J. of Mining Sci. and Tech., 34, 1741-1752.
- FERNANDEZ, R.R. SOHN, H.Y., LEVIER, K.M., 2000, Process for Treating Refractory Gold Ores by Roasting Under Oxidizing Conditions, Miner. Metall. Process., 17(1), 1-6.
- FINKELSTEIN, N.P., POLING, G.W., 1977, The role of dithiolates in the flotation of sulfide minerals, Mineral Sci. Eng.
- GARDNER, J.R., WOODS, R., 1974, An electrochemical investigation of contact angle and of flotation in the presence of alkyl xanthates, I, platinum and gold surfaces, Aus. J. Chem. 27, 2139-2148.
- GOKTEPE, F., 2002, Effect of pH on pulp potential and sulfide mineral flotation, Turk. J. Eng. Environ. Sci., 6, 309 318.
- JHA, M.C., 1987, Refractoriness of certain gold ores to cyanidation Probable causes and possible solutions, Miner. Process. Extr. Metall. Rev., Vol. 2, 331-352.
- KOMNITSAS, C., and POOLEY, F.D., 1989, *Mineralogical Characteristics and Treatment of Refractory Gold Ores*, Miner. Eng., 2(4), 449-457.
- La BROOY, S.R., LINGE, H.G., WALKER, G.S., 1994, Review of gold extraction from ores, Miner. Eng., 7(10), 1213-1241.
- LEE, S., GIBSON, C.E., GHAHREMAN, A., 2021, Flotation of carbonaceous matter from a double refractory gold ore: the effect of MIBC on flotation performance and kinetics, Minerals, 11(9), 1021.
- MILLER, J.D., MISRA, M., GOPALAKRISHNAN, S., 1986, Gold flotation from Colorado river sand with air sparged hydrocyclone, Miner. Metall. Process, 3, 145-148.
- NAGARAJ, D.R., 1997, Developments of new flotation chemicals, Trans. Indian Inst. Met., 50(5), 355-363.
- NAKHAEI, F., IRANNAJAD M., 2018, Reagents types in flotation of iron oxide minerals: A review, Miner. Process. Extr. Metall. Rev., 39(2), 89-124.
- O'CONNOR, C.T., BOTHA, C., WALLIS, M.J., DUNNE, R.C., 1988, *The role of copper sulfate in pyrite flotation*, Miner. Eng., 1(3), 203-212.
- O'CONNOR, C.T., DUNNE, R.C., 1991, The practice of pyrite flotation in South Africa and Australia, Miner. Eng., 4(7-11), 1057-1069.
- OWUSU, C., AGORHOM, E.A., FOSU, S., BUDU-ARTHUR, E., 2020, Adsorption Studies of Sulphidic refractory gold ore, Powder Technology, 310-316.
- SOLTANI, F., DARABI, H., BADRI, R. AND PIROZ, Z., 2014, *Improved recovery of a low-grade refractory gold ore using flotation-preoxidation-cyanidation methods*, International Journal of Mining Science and Technology 24(4).

SPICKELMIER, K., 1993, Round Mountain Halves Its Cutoff Grade, Miner Eng. (194) 41-48.

- SUN, Z.X., FORSLING, W., 1997, *The degradation kinetics of ethyl-xanthate as a function of pH in aqueous solution*, Miner. Eng. 10 (4), 389–400.
- TEAGUE, A.J., VANDEVENTER, J.S.J., SWAMINATHAN, C., 1999a, A conceptual model for gold flotation, Int. J. Miner. Process., 1001-1019.
- VALSIVIESO, A.L., 2006, Flotation and depression control of arsenopyrite through pH and pulp redox potential using *xanthate as the collector*, Int. J. Miner. Process., 81(1), 27-34.
- VAUGHAN, J. P., 2004, *The process mineralogy of gold: The classification of ore types*, JOM, Metals and Materials Society, 56, (7), 46-48.
- WOODS, R., BASILIO, C.I., KIM, D.S., YOON, R.H., 1994, *Chemisorption of ethyl xanthate on silver-gold alloys*, Coll. Surf. A: Physicochem. Eng. Aspects 83, 1-7.
- ZAGHLOUL, K., 2020, Mineralogical investigation of gold ores, Egyptian Mineral Resources Authority.
- ZHOU, J., Jago, B., MARTIN, C., 2004, *Establishing the process mineralogy of gold ores*, SGS Minerals, Technical Bulletin.