Gold Process Mineralogy: Objectives, Techniques, and Applications

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The extractive metallurgy of gold is largely driven by mineralogical factors such as gold particle size; association with other minerals; coatings; presence of cyanicides, oxygen consumers, and preg-robbers; presence of refractory gold minerals; and locking of submicroscopic gold in sulfide and sulfarsenide mineral structures. Gold process mineralogy addresses all issues related to gold ore processing by the detailed study of an ore or a mill product. The methodology is widely used as a predictive tool in feasibility studies and during the process development stage, and as a trouble-shooting tool for mineral processing and hydrometallurgical operations.

INTRODUCTION

Based on the gold recovery and mineral processing techniques required, gold ores are commonly classified into two major categories: free-milling and refractory ores. Typically, free-milling ores are defined as those where over 90% of gold can be recovered by conventional cyanide leaching. Refractory ores give low gold recoveries or give acceptable gold recoveries only with the use of significantly more reagents or more complex pre-treatment processes.[1]

Generally, placers, quartz vein gold ores, oxidized ores, and silver-rich ores are free-milling and gold can be recovered by gravity and/or direct cyanide leaching. Some epithermal deposits may be free-milling (such as the oxidized portion) but more commonly contain significant amounts of sulfides in which gold occurs as micrometer-sized inclusions or as submicroscopic gold and are therefore refractory. When the silver grade in an ore is high (>10 g/t) and/or the gold is present as so-called "küstelite" (Au<50%, Ag>50%) or electrum (Au 50–75%, Ag

25–50%), the processing may need to be modified. The greater reactivity of silver can influence the behavior of gold in flotation, leaching, and/or recovery processes. Electrum with a high silver content may give poor gold extraction due to tarnishing of the silver. Küstelite often gives low recovery by flotation due to the formation of a hydrophilic silver-rich coating. Iron sulfide ores and

arsenic sulfide ores host different proportions of free-milling and refractory gold.[2] Gold in free-milling sulfide ores can be recovered by whole-ore cyanidation or some combination of flotation and cyanidation. Acceptable extraction of refractory gold can only be achieved by employing a pre-oxidation process prior to cyanide leaching. Antimony, bismuth sulfide, and telluride
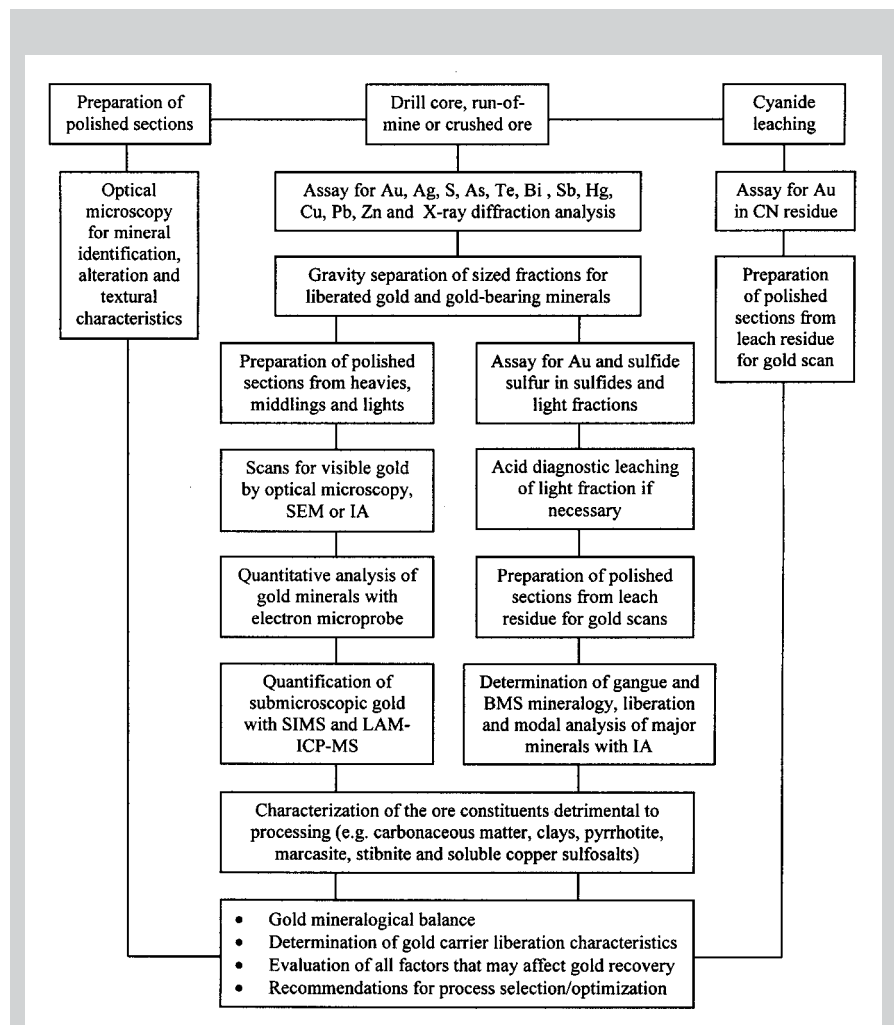

Figure 1. The general procedure used for gold process mineralogical study (modified from Zhou et al.)[1]

gold ores are often somewhat refractory due to the presence of slow-dissolving gold minerals such as aurostibite ($AuSb_2$), maldonite (Au_2Bi), and gold tellurides. Carbonaceous sulfide ores are the typical refractory ores because the gold is fine-grained, and, usually, is predominantly associated with the sulfide minerals (pyrite and arsenopyrite) that are present in carbonaceous ores. Gold in carbonaceous sulfide ores is usually recovered by pre-oxidation followed by cyanidation with or without prior concentration by flotation. Gold recovery from the carbonaceous sulfide ore is more difficult not only because the gold is fine-grained and locked in sulfide minerals but also because the gold can be robbed from the cyanide solution by the carbonaceous matter.[3] At Barrick's Goldstrike Mine, where gold occurs in pyrite in refractory sulfide ore and double-refractory sulfide/carbonaceous ore, gold ores are pretreated by autoclave and roaster prior to cyanide leaching.[4,5] In the Jinya Carlin-type gold deposit in China, gold occurs mainly as submicroscopic gold in arsenopyrite and pyrite and is recovered by roasting a flotation concentrate followed by cyanidation.[6]

OBJECTIVES

Process mineralogy is often used to predict the response of a gold ore to the various candidate processes. In addition, during the processing of a gold ore, periodic mineralogical analyses of ore feed and mill products are needed to determine the nature of the problem if the gold recovery is lower than expected. Therefore, a routine process mineralogical study of gold ores normally includes some or all of the following objectives:[1]

- Determine gold and silver grade by fire assay and analyze S, As, Te, Bi, Sb, Hg, Cu, Pb, Zn, and C for balancing the gold and determining the abundance of common gold-bearing minerals
- Determine the nature of visible gold, including identification and location of all gold minerals, their size distributions, compositions, liberation characteristics, and associations with other minerals for predicting the grinding fineness and possible response of the ore to conventional gold recovery techniques
- Quantify the fractions of liberated gold, gold associated with sulfides, gold associated with oxides/silicates, and gold associated with carbonaceous material (if present) for estimating the maximum amount of gold that can be recovered by gravity, flotation, and direct cyanidation or a combination of these processes
- Quantify the submicroscopic gold in sulfide and other minerals for determining the amount of gold that can only be recovered by employing preoxidation or bio-leaching
- Determine any other valuable metals (such as silver and copper) and deleterious minerals (e.g., talc, serpentine, graphite, cyanicides, oxygen consumers, and water-soluble minerals) in terms of species, amount, and distribution, liberation characteristics for predicting their possible response to the common mineral processing techniques, and investigate their mineral processing requirements
- Evaluate the preg-robbing potential of carbonaceous matter and gangue minerals
- Determine the reason(s) for high gold losses to tailings and opportunities to improve gold recovery

To reach these objectives, an investigation procedure involving conventional and advanced mineralogical techniques is usually employed (Figure 1).

TECHNIQUES

Table I lists some techniques commonly used in gold process mineralogical studies including conventional techniques and advanced instrumental techniques. These techniques can be used individually, but most often, several techniques will be used collectively in a process mineralogical study due to the complexity of the issue being studied.

It is worthwhile to point out that some conventional techniques such as fire assaying, gravity concentration, and ore microscopy are just as important as advanced microbeam techniques. Fire assaying is the traditional method of gold analysis and is an integral element in many parts of a typical gold process mineralogical study, as it provides bulk gold balance information, complementing the mineralogical information

Table I. Techniques Commonly Used in Gold Process Mineralogy*

| No.	Technique	Abbreviation	Detection Limit	Application
1	Fire assay	FA	0.1–50 g/t Au	Determination of gold in all forms
2	Quadruple 1 t FA-AA assay	FA-AA	0.001 g/t Au	Determination of gold in all forms
3	Cyanide leaching	CN	—	Determination of the amount of recoverable gold by cyanidation
4	Gravity concentration	GC	—	Concentration of gold and gold-bearing minerals
5	Acid diagnostic leaching	ADL	—	Determination of gold associated with carbonates, sulfides and silicates
6	Optical microscopy	OMS	~0.5 μm	Systematic scan for gold particles, mineral identification, alteration, and textural characteristics study
7	Automated digital imaging system	ADIS	—	Gold scan and measurement
8	Scanning electron microscope	SEM	Semi-quantitative	Gold scan, mineral identification, and surface morphological study
9	Quantitative evaluation of material by scanning electron microscope	IA (Image analyzer)	1.5 to 3 μm	Gold scan, mineral identification, liberation, surface morphological study, and modal analysis
10	Electron probe microanalysis	EPMA	0.1% EDX 0.02% WDX	Compositional analysis of gold and associated minerals
11	Dynamic secondary ion mass spectrometry	D-SIMS	sub-ppm	Quantification and mapping of gold in sulfides and FeO_x
12	Proton-induced x-ray emission	μ-PIXE	ppm	Quantification and mapping of gold in sulfides and silicates
13	Laser ablation microprobe inductively coupled plasma mass spectroscopy	LAM-ICP-MS	ppb	Quantification of gold in sulfides, silicates, and oxides
14	Time-of-flight laser ion mass spectrometry	TOF-LIMS	ppm	Quantification of surface gold and analysis of surface chemistry

* Modified from Zhou et al.[1]
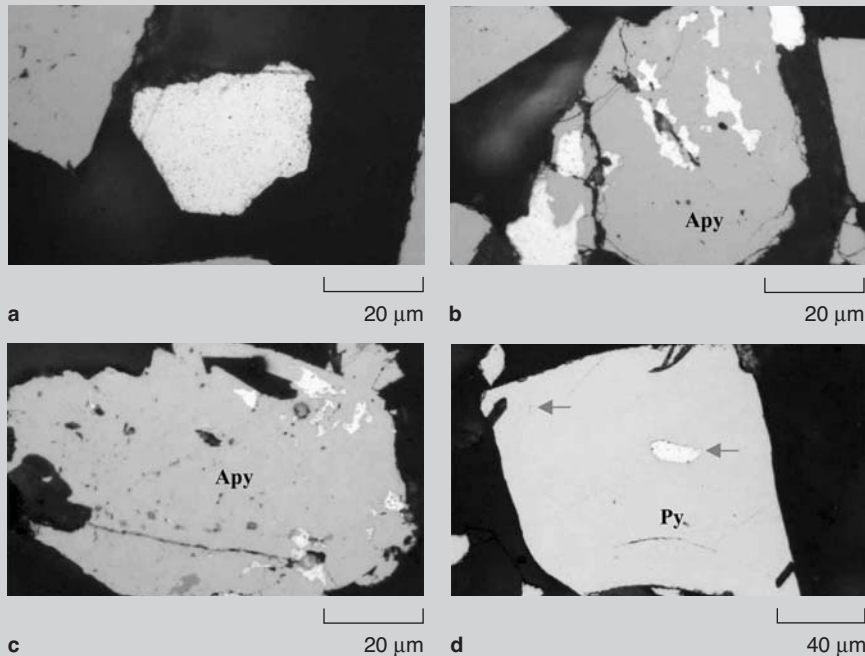
Figure 2. Photomicrographs showing the mode of occurrence of microscopic gold. (a), liberated; (b) and (c), attached to and locked in arsenopyrite (Apy); and (d), locked in pyrite (Py).

obtained from the other techniques. The most common gravity concentration techniques in gold process mineralogy are heavy liquid separation, superpanning, the Mozley table, and the newly developed hydroseparation technique.[7–9] Wilfley tables and Knelson concentrators are also used when a large sample is treated. Among these techniques, superpanning and hydroseparation have been proven to be the most effective in sample preparation for gold mineralogical study techniques.[1,7,8] By using a superpanner, a small amount of tip (i.e., pan concentrate, usually 100–500 mg) is obtained for gold examination. Usually, all liberated gold mineral particles are concentrated into the tip, and a clean sulfide fraction and silicate fraction are obtained for gold assays.[1] The hydroseparation technique is efficient in concentrating heavy minerals at factors up to 10,000 times. Hydroseparation is particularly useful in process mineralogical studies of platinum-group-elements, gold, and silver ores for samples from 5 g to 2,000 g but may find applications for other ores (e.g., scheelite and beach placers).[7] Reflected light microscopy remains the most fundamental and widely used method in gold process mineralogy. The resolution limit of optical microscopy is about 2 μm for liberated gold particles

and ~0.5 μm for gold inclusions when a magnification of 500× is used. The advantage of using optical microscopy is that it identifies gold and other minerals by reflectivity, color, hardness, cleavage, and other mineralogical characteristics. While searching for gold, the information on gold and bulk mineralogy (such as the mineralogical composition and liberation characteristics) will also be

obtained. This is particularly important when the ore or mill product contains more than one gold mineral/carrier and other valuable minerals. It is also important when gold occurs mainly as inclusions in other minerals, because the size of the host mineral can also be measured for liberation study statistics.

Advanced instrumental techniques employed in gold process mineralogical study include scanning electron microscopy (SEM); SEM-based quantitative image analysis (MP-SEM-IPS, IA-KS400 [Zeiss Vision], quantitative evaluation of minerals by scanning electron microscope, and mineral liberation analysis); electron probe microanalysis; secondary ion mass spectrometry (SIMS); particle-induced x-ray emission (PIXE); laser ablation microprobe inductively coupled plasma mass spectroscopy (LAM-ICP-MS); etc. Scanning electron microscopy and image analysis are usually used for morphological study and fine-grained gold search.[10] Quantitative image analysis is also used to determine the modal weight percent of the major minerals needed for gold balancing. Three different SEM-based image analyzers are currently available. Electron probe microanalysis is mainly used for the quantitative determination of gold and associated minerals. The
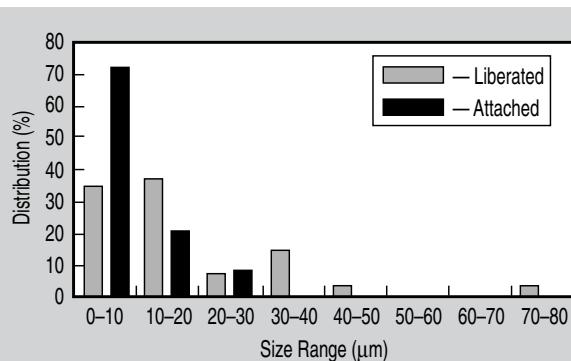

Figure 3. The size distribution of liberated and attached gold particles. The majority of gold particles were less than 40 μm in size.
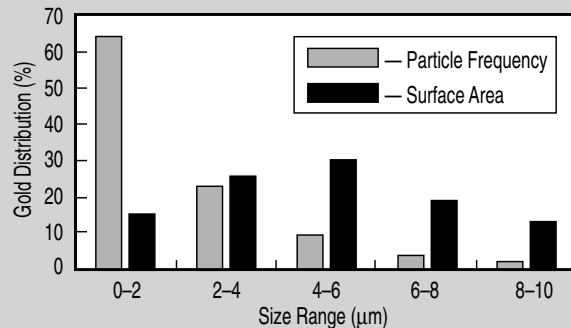

Figure 4. The size distribution of gold locked in sulfide minerals. Finer grinding is required to recover these gold inclusions.
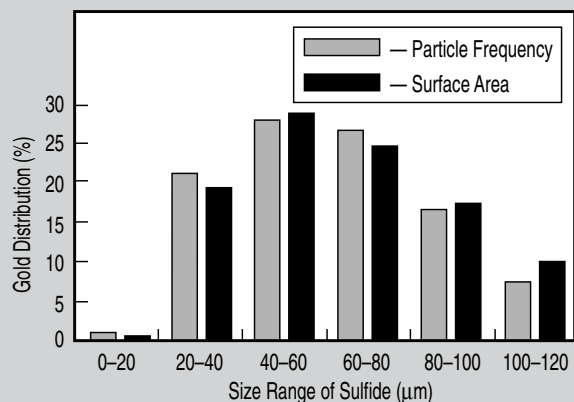
Figure 5. The distribution of locked gold vs. size of gold-bearing sulfide minerals. The majority of gold-bearing sulfide minerals ranged from 20 μm to 100 μm (accounting for ~90% of total particles and surface area), indicating that 20 μm of regrinding fineness will be required to liberate or expose the gold inclusions locked in sulfide minerals.

techniques of SIMS, PIXE, and LAM-ICP-MS are used for the quantification of submicroscopic gold in sulfide and gangue minerals.[1,2,6,11–14] The TOF-LIMS technique is used for the quantification of gold adsorbed on the surface of carbonaceous matter and other minerals and for the determination of inorganic surface composition.[15]

METALLURGICAL APPLICATIONS

Iron sulfide ores and arsenian sulfide ores host different proportions of free-milling and refractory gold. Gold in free-milling sulfide ores occurs as coarse- and fine-grained particles and can be recovered by whole-ore cyanidation or some combination of gravity concentration, flotation, and cyanidation. Gold in refractory sulfide ores often occurs as fine-grained inclusions (visible gold), chemically bonded[16,17] (submicroscopic gold), or both in pyrite and arsenopyrite, and acceptable recovery of gold can only be achieved by employing a pre-oxidation process prior to cyanide leaching.

For example, gold in a sulfide ore containing approximately 20 g/t gold, 2% arsenopyrite, and 1% pyrite occurred as both microscopic gold and submicroscopic gold. Microscopic gold was determined to be native gold with 3.2% silver and 8.2% mercury. Gold was deported as liberated gold particles (accounting for 18% of the head assay), sulfide minerals, mainly arsenopyrite,

(accounting for 74% of the head assay) and non-sulfide minerals (accounting for 8% of the head assay) when the ore was ground to 80% passing 75 μm (Figure 2). A mineralogical study showed 55 liberated gold particles (ranging from 3 μm to 80 μm), 42 gold particles attached to sulfide minerals (ranging from 1 μm to 26 μm), and 220 gold inclusions locked in sulfide minerals, ranging from 0.5 μm to 9 μm in size (Figures 3 and 4). Metallurgically, liberated gold and attached gold are recoverable by flotation and/or direct cyanidation, while the recovery of gold locked in sulfide minerals requires finer grinding. Figure 5 shows that the majority of gold-bearing sulfide minerals (~90%) ranged from 20 μm to 100 μm, indicating that regrinding to a mean size of 20 μm will be adequate to liberate or expose those gold inclusions locked in sulfide minerals (mainly arsenopyrite). In addition to searching for microscopic gold, SIMS analysis was conducted to quantify the submicroscopic gold in arsenopyrite and pyrite. Secondary ion mass spectrometry data showed that arsenopyrite was the major submicroscopic gold carrier in the ore. The concentration of gold in arsenopyrite was 6.8–5,902 ppm (minimum detection limit [MDL] = <171 ppb gold in arsenopyrite), with an average of 1,051 ppm. Gold concentration in pyrite was lower than the SIMS detection limit (MDL = <259 ppb gold in pyrite), indicating that pyrite was not

an important carrier for submicroscopic gold in this ore. Submicroscopic gold in arsenopyrite is not recoverable by finer grinding or direct cyanidation. It can only be recovered by pre-oxidation, followed by cyanidation with or without prior concentration by flotation.

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