ESTABLISHING THE PROCESS MINERALOGY OF GOLD ORES

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ABSTRACT

From the perspective of metallurgical processing, gold ores can be classified into free-milling and refractory ores. Their extractive metallurgy are largely driven by mineralogical factors such as: gold particle size, association with other minerals, coatings and rimmings, presence of cyanicides, oxygen consumers and preg-robbers, presence of refractory gold minerals and locking of submicroscopic gold in sulfide mineral structure etc. Gold process mineralogy helps address issues and problems related to gold ore processing. It provides useful information on process selection, flowsheet development, recovery improvement and reagent consumption optimization. By combining classic mineralogical techniques, modern instrumental analysis and diagnostic metallurgy, the mineralogist is able to balance the various types of gold occurrence in an ore. This paper will provide a broad review of gold process mineralogy and the techniques available, and use case studies to describe how they can be used together, to provide the complete picture of gold process mineralogy in an ore. Examples will be used where applicable.

INTRODUCTION

Since the early 1980's, a great deal of work has been done in the characterization of gold ores, particularly refractory ores (Gasparrini, 1983; Wang, 1984; Hausen, 1985; Haines, 1986; Henley, 1989; Chryssoulis et al., 1990; Wang et al., 1992, 1994; Kojonen, 1999; Simon et al., 1999; Hong et al., 2000; Pals et al, 2003). Process mineralogy has come into its own as a respected inter-discipline in the fields of mineralogy and metallurgy - a subject that occupies an important place in both research and industry. As the free-milling gold ores are being depleted and more refractory ores are being discovered and processed, gold process mineralogy receives more and more attention from both the mineralogist and metallurgist as it helps to solve various problems encountered during gold ore processing. Steadily rising gold prices are also stimulating the need for gold process mineralogy due to the increasing demand for and production of the yellow metal. At SGS Lakefield Research, gold process mineralogy studies are conducted routinely on all types of gold ores and mill products to assist in a wide variety of metallurgical projects. This paper will briefly discuss the gold ore types and gold mineralogy, review the common mineralogical factors affecting gold extractive metallurgy and the techniques available to gold process mineralogy, introduce the procedure employed at SGS Lakefield Research, and provide some case studies to give a complete picture of gold process mineralogy.

GOLD ORES AND MINERALS

GOLD ORE TYPES

Gold ores are commonly classified by the metallurgist 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 are defined as those that give low gold recoveries or give acceptable gold recoveries only with the use of significantly more reagents or more complex pre-treatment processes. Based on the mineralogical characteristics and mineral processing techniques required, gold ores can be classified into 11 types (Table 1).

Some metallurgical implications to these gold ore types are summarised below:

Placers, quartz vein gold ores and oxidized ores: Generally, placers, quartz vein gold ores and oxidized 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 tiny inclusions or submicroscopic gold and are therefore refractory.

Silver-rich ores and copper sulfide ores: Silver-rich ores and copper sulfide ores are often free-milling, but when the silver grade is high (>10 g/t) and/or the gold is present as electrum, the processing may need to be modified. The greater reactivity of silver

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Table 1: Gold Ore Types and Gold Occurrence

#	ORE TYPE	MODE OF OCCURRENCE OF GOLD	EXAMPLE
1	Placers	Gold is easily liberated or has been liberated prior to processing, and normally ranges from 50-100 μm in size.	Witwatersrand (South Africa), Jacobina (Brazil), Tarkwa (Ghana)
2	Quartz vein-lode ores	Gold occurs mainly as native gold in quartz- veins, lodes or stockworks, some tellurides and occasionally aurostibite and maldonite. Commonly occurs as liberated gold particles but some disseminated gold may be present.	Timmins Camp: Hollinger - McIntryre (Canada), Homestake (USA), Bendigo (Australia), Shandong Camp: Linglong (China), Muruntau (Uzbekistan)
3	Oxidized ores	Gold usually occurs as either liberated or in the alteration products of sulfide minerals, and the degree of gold liberation is generally increased by oxidation	Pierina (Peru), Yanacocha (Peru), Yilgarn region (Australia)
4	Silver-rich ores	Gold commonly occurs as electrum, although kustelite may be present in some ores. Native silver may be present.	Rochester, Candelaria and Tombstone (USA), La Coipa (Chile)
5	Copper sulfide ores	Gold occurs as coarse liberated particles and fine particles locked in pyrite and copper sulfides.	Grasberg and Batu Hijau (all in Indonesia), Bulyanhulu (Tanzania), Oyu Tolgoi (i.e. Turquoise Hill) (Mongolia)
6	Iron sulfide ores	Gold occurs as liberated particles, attachments to and inclusions in sulfide (commonly in pyrite, and less commonly in marcasite and pyrrhotite, and as submicroscopic gold in sulfide minerals	Many sulfide ores, including Carlin-type gold ores
7	Arsenic sulfide ores	Gold occurs as liberated particles and inclusions, and submicroscopic gold in arsenopyrite and oxidized products.	Giant Yellowknife, Campbell Mine (Canada), Sao Bento (Brazil) and Carlin-type ores
8	Antimony sulfide ores	Gold occurs mainly as native gold, with minor to moderate amount of aurostibite, either liberated or locked in sulfides.	Big Bell (Australia), Hechi (China), Manhattan (USA)
9	Bismuth sulfide ores	Gold occurs mainly as native gold, with minor to moderate amounts of maldonite. Submicro-scopic gold can also be present in sulfides.	Maldon (Australia), Tongguan (China), Pogo (USA)
10	Telluride ores	Gold occurs as native gold and gold tellurides, either liberated or locked in sulfides. Submicroscopic gold may be present.	Cripple Creek (USA), Emperor (Fiji), Kalgoorlie (Australia), Kumtor (Kyrgyzstan)
11	Carbonaceous - sulfidic ores	Gold occurs mainly as fine-grained gold particles and submicroscopic gold in sulfides, and surface gold absorbed onto the surface of carbonaceous matter and FeOx.	Carlin, Cortez, Getchell, Betze and Meikle (all in the USA), Jinya, Gaolong, Lannigou and Donbeizhai (all in China)

can influence the behaviour 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 (Fleming, 1998). The presence of copper in the ore at above ±0.3% concentration may make direct cyanidation uneconomic without re-treating the $Cu(CN)_2$ formed in leaching, through processes such as SART and Hannah.

Iron sulfide ores and arsenic sulfide ores: Iron sulfide ores and arsenic sulfide ores host different proportions of non-refractory and refractory gold.

Gold in non-refractory 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 gold ores: Antimony, bismuth sulfide and telluride gold ores are often somewhat refractory due to the presence of slow-dissolving gold minerals such as aurostibite, maldonite and gold tellurides.

Carbonaceous ores: The gold is fine, and, usually, is predominantly associated with the sulfides (pyrite or arsenopyrite) that are present in carbonaceous ores. Gold in these types of ores is usually recovered by pre-oxidation to dissolve the host sulphides, followed by cyanidation with or without prior concentration by flotation. Some is in the form of colloidal size grains (<0.1 μm) in carbonates or microcrystalline quartz particles (Fleming, 1998). Gold recovery from the carbonaceous sulfidic ore is more difficult because the gold is "robbed" from the cyanide solution by the carbonaceous matter (Wan, 2001).

A notable example of such a double-refractory carbonaceous sulfide ore is at Barrick's Goldstrike Mine where gold occurs in pyrite in refractory sulfide ore and double-refractory sulfidic/carbonaceous ore. These ores are pretreated by autoclave and roaster prior to cyanide leaching (Thomas et al., 2000; Wickens et al., 2003). 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 (Wang et al., 1994).

GOLD ORES AND MINERALS

According to the mode of occurrence, gold is classified as three categories: microscopic gold, submicroscopic gold and surface-bound gold (Table 2). Gold minerals in this paper are defined as the minerals in which gold is present as a main constituent (e.g. native gold and electrum). Gold carriers are defined as both the gold mineral and the mineral in or on which gold occurs only in trace amount (such as pyrite and arsenopyrite).

MICROSCOPIC GOLD

Microscopic gold, also known as visible gold, comprises gold alloys, gold tellurides, gold sulfides, gold selenides, gold sulfotellurides and gold sulfoselenides etc. Native gold (Au) and electrum (Au, Ag), found in various types of gold deposits, are the two most common and most important gold minerals. Other gold minerals of economic significance in some gold deposits include kustelite (AgAu), auricupride (Cu_3Au), tetraauricupride (CuAu), calaverite ($AuTe_2$), krennerite ($(Au, Ag)Te_2$), aurostibite ($AuSb_2$) and maldonite (Au_2Bi).

Microscopic gold in primary ores occurs as pristine grains of varied size and shape in fractures and microfractures, or as attachments to and inclusions in other minerals. Figure 1 presents some common examples of gold occurrences observed in ore and mill products. Table 3 lists all gold minerals along with their compositions.

Table 2: Classification of Gold by Forms and Carriers

FORM	MICROSCOPIC GOLD	SUBMICROSCOPIC GOLD	SURFACE GOLD
NATURE	Visible under microscope	Invisible under microscope	Invisible under microscope
CARRIER	All gold minerals: native gold and electrum are the most common ones, and calaverite, aurostibite, and maldonite are less common	Arsenopyrite, Pyrite, Marcasite, Chalcopyrite, Enargite, Realgar, Loellingite, Acanthite FeOx, Clay minerals	Carbonaceous matter, FeOx, Stained quartz, Activated carbon, Clay minerals, Wood chips, Pyrite, Arsenopyrite

SUBMICROSCOPIC GOLD

Gold that is invisible under optical microscope and scanning electron microscope is referred to as submicroscopic gold or invisible gold. Submicroscopic gold is the major form of gold in:
• Carlin-type gold deposits (such as Carlin, Jerritt, Goldstrike, Getchell in the USA; Jinya, Gaolong, Donbeizhai and Lannigou in China) and
• some epithermal gold deposits in South America.

Gold usually occurs in these ores as discrete particulates (<0.1 µm in diameter) within sulfide minerals (mainly in pyrite and arsenopyrite) (Hausen, 1981; Radtke, 1985; Hausen et al., 1986; Wang et al., 1992, 1994).
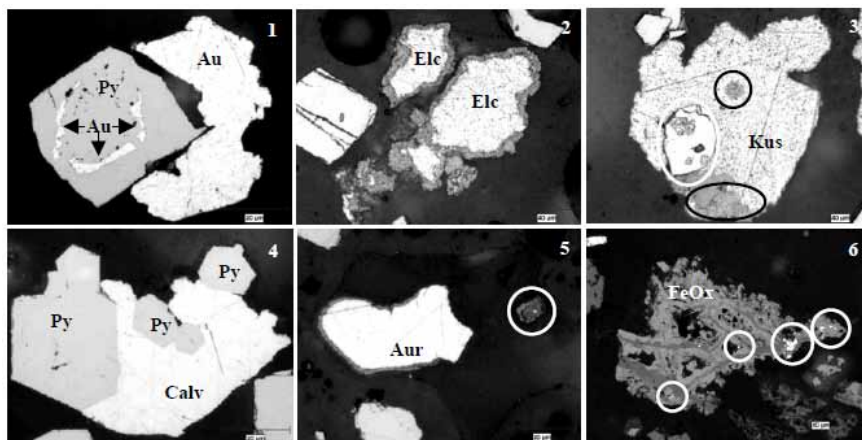

Figure 1: Some examples of gold occurrence: 1 - exposed native gold (Au) and gold locked in pyrite (Py); 2 - electrum (Elc) with acanthite rims (gray); 3 - kustelite with acanthite inclusion and attachment (gray particle in black circle), it also has a pyrite insert with some fine-grained electrum inclusions (inside white circle); 4 - calaverite (Calv) associated with pyrite; 5 - unleached aurostibite (Aur) with a secondary rim (deep brown) and an altered aurostibite (inside white circle) from a cyanide leach residue; 6 - native gold (inside white circles) locked in FeOx from a flotation tail.

In gold ores, pyrite and arsenopyrite often occur in three morphological types: coarse, porous (blastic) and fine-grained. Framboidal and microcrystalline pyrite are also observed in some gold deposits. Generally, the order of concentration of gold in pyrite and arsenopyrite is: fine-grained>porous>coarse-grained (Figures 8 & 9). In some gold deposits, zoned pyrite contains a high gold concentration, and gold in the outer accretion zone is often higher than that in the core. Gold concentration in pyrite and arsenopyrite ranges from below one ppm to several hundred ppm. Possibly the most Au-rich pyrite was reported from the Emperor gold deposit in Fiji, which contained up to 11,057 ppm Au (Pals et al, 2003). Gold concentrations in arsenopyrite of up to 15,200 ppm have been reported (Chryssoulis et al., 1990). Other submicroscopic gold carriers include chalcopyrite (Cook et al., 1990), loellingite (Neumayr et al., 1993), marcasite, FeOx (in oxidized ores or calcines), realgar and clay minerals (Chao et al., 1987; Wang et al., 1994). Solid solution gold and colloidal gold are the two major forms of submicroscopic gold.

SURFACE GOLD

Surface-bound gold is the gold that was adsorbed onto the surface of other minerals during the mineralization and subsequent oxidation or metallurgical processing. Surface gold is also invisible under optical and electron microscope, and can only be detected by LIMS (described later in this paper). Principal surface gold carriers in the ore include FeOx, stained quartz, carbonaceous matter, clay minerals and wood chips (Table 2).

FACTORS AFFECTING GOLD EXTRACTIVE METALLURGY

The major mineralogical factors that affect gold extractive metallurgy are discussed briefly below.

Gold Grain Size: The grain size of the gold mineral can be a significant factor driving the efficiency of gold recovery processes. Coarse gold may be incompletely leached (or may become trapped upstream of the cyanidation circuit), or not carried by bubbles in flotation. Ultrafine gold is not well recovered by gravity or flotation techniques. When gold is very fine (< 10 μm) and associated with sulfide minerals, cyanidation performance may also be poor (Marsden et al., 1992). Encapsulation of visible gold in sulfide and silicate minerals is a common cause for gold losses.

Submicroscopic gold: Submicroscopic gold, described early, is a significant source of lost gold from many cyanidation operations. The finest grained sulphides usually contain the highest concentrations of solid-solution gold. Consequently, the problem is often exacerbated by poor liberation of the ultra-fine, gold hosted sulphides (Hausen, 1985; Radtke, 1985; Wang et al. 1994; Simon et al., 1999).

Coatings and rimmings mainly affect gold extraction by flotation and cyanidation. These coatings and rimmings may be iron oxides or hydroxides (limonite or goethite), which are formed by oxidation, dissolution and precipitation reactions. In addition, sulfide ions react with gold to form insoluble aurous sulphide coatings (Fink et al., 1950). Similar

Table 3: Gold Minerals

GROUP NAME	MINERAL	FORMULA	AU CONTENT (WT.%)
Gold Alloys	Native gold	Au	>75
	Electrum	(Au, Ag)	50-75
	Kustelite	(Ag, Au)	<50
	Aurostibite	AuSb2	43-51
	Maldonite	Au2Bi	63-68
	Auricupride	Cu3Au	50-56
	Tetraauricupride	AuCu	70-76
	Weishanite	(Au, Ag)3Hg2	56.9
	Yuanjiangite	AuSn	62.4
	Hunchunite	Au2Pb	62.6
	Anyuiite	AuPb2	27-33
Gold Telluride	Calaverite	AuTe2	39-44
	Krenerite	(Au, Ag)Te2	30-44
	Montbrovite	(Au, Sb)2Te3	38-45
	Muthmannite	(Ag, Au)Te	23-35
	Kostovite	CuAuTe4	~25
	Sylvanite	(Au, Ag)2Te4	24-30
	Petzite	Ag3AuTe2	19-25.4 3-
	Hessite	(Ag, Au)2Te	14.7~7-
Gold Sulfotelluride	Nagyagite	Au2Pb13Sb3Te6S16	10
	Buckhornite	AuPb2BiTe2S3	17.0
Gold Lead-telluride	Bessmertnovite	Au4Cu(Te,Pb)	68-88
	Bogdannovite	(Au, Te, Pb)3(Cu, Fe)	57-63
	Bilibinskite	Au3Cu2PbTe2	40-66
Gold Sulfide	Criddleite	TlAg2Au3Sb10S10	22-23
	Liujiyinite	Ag3AuS2	18.6-36
	Uytenbogaardtite	Ag3AuS2	27-35
Gold Selenide	Fischesserite	Ag3AuSe2	~27.3
Gold Sulfoselenide	Petrovskaite	AuAg(S, Se)	~56-61
	Pensinite	(Ag, Cu)4Au(S, Se)4	~25

passivation may occur in the presence of thioarsenite and thioantimonite ions (Heldey et al., 1958).

Silver in gold minerals. Except occurring as silver minerals, silver in gold ores is often present in electrum, and occasionally in kustelite. Silver-rich electrum and kustelite tarnish quickly in air, and form a silver sulfide layer of 1-2 μm in thickness in the presence of sulfide ions, which can limit the access of cyanide solution. Such coatings are somewhat hydrophilic, particularly if further oxidation to silver sulfate or silver oxide occurs. This may hamper recovery by flotation (Jilin Institute of Metallurgy, 1978).

Gold tellurides, aurostibite and maldonite. Gold tellurides, aurostibite and maldonite are generally considered refractory because of their slow-dissolving nature in cyanide solutions.

Presence of cyanide and oxygen consumers. Many gold ores contain minerals that react in cyanide solution, consuming oxygen or cyanide or both, and negatively influencing the rate or extent of gold leaching. The most common interfering minerals are the sulfides of iron, arsenic, antimony, copper, zinc and tellurium (Fleming, 1998).

Gangue mineralogy. This takes several forms:

• Quartz and many silicate minerals are essentially inert but can dissolve to some extent in strongly acidic conditions, such as those encountered in bio-oxidation, to form a gelatinous silicate which may coat exposed gold surfaces and is hard to filter. Chlorite is soluble in sulfuric acid and forms products that are typically difficult to filter.

• Carbonates react readily with sulfuric acid to form the respective sulfates, e.g. gypsum and magnesium sulfate. These reactions often consume significant amount of acid. For example, 1% limestone in an ore requires 10 kg H2SO4/t ore. The reaction products of carbonate decomposition may also cause problems downstream with increased slurry viscosities, coatings on exposed gold surfaces and scale accumulation in pipes and reactors (Marsden et al., 1992).

• Carbonaceous matter and other materials can reduce gold extraction during cyanide leaching by adsorbing dissolved gold from the pregnant solution, as described early. Other materials identified as preg-robbers are gold-adsorbing pyrophyllite and shale in Witwatersrand ores (Corrans et al., 1985). Wood chips resulting from underground blasting and wood-support systems (Petersen et al., 1997), and FeO+MgO+Al2O3 in shales from Beatrix gold mine in South Africa (Vuuren et al., 2000) are also potential preg-robbers.

• Solid-solution gold analysis should not always be restricted to the sulphides, an example of this being cited in the 1989 Cyanamid Minerals Handbook (Cyanamid, 1989):

A flotation plant had been recovering gold by concentrating free gold and gold-bearing pyrite (gold occurs as fine inclusions). Gold recovery was very low, however. A mineralogical examination of head and tailings samples showed that gold was also very finely locked in limonite which had replaced some of the pyrite. The limonite was being rejected to the tailings along with its inherited gold inclusions.

METHODOLOGY

INVESTIGATIVE PROCEDURE

A routine process mineralogical study of gold ore normally includes some or all of the following objectives:

1. Determination of Au and Ag by fire assay and analysis of S, As, Te, Bi and Sb etc.
2. Determination of the total visible gold, including identification and location of all gold minerals, their size distribution, composition, liberation characteristics and associations with other minerals.
3. Quantification of the fractions of liberated gold, gold associated with sulfides, gold associated with oxides/silicates, and gold associated with carbonaceous material (if it occurs).
4. Quantification of submicroscopic gold in sulfide and other minerals.
5. Determination of any other valuable minerals (such as silver and copper) and deleterious minerals (e.g. talc, serpentine, graphite, cyanicides, oxygen consumers, and water- soluble minerals) in terms of amount, type and distribution.
6. Evaluation of preg-robbing potential of carbonaceous matter and gangue minerals.

To reach the objectives listed above, an investigation procedure involving conventional and advanced mineralogical techniques (Figure 2) should be used. These are described in more detail in the ensuing sections.
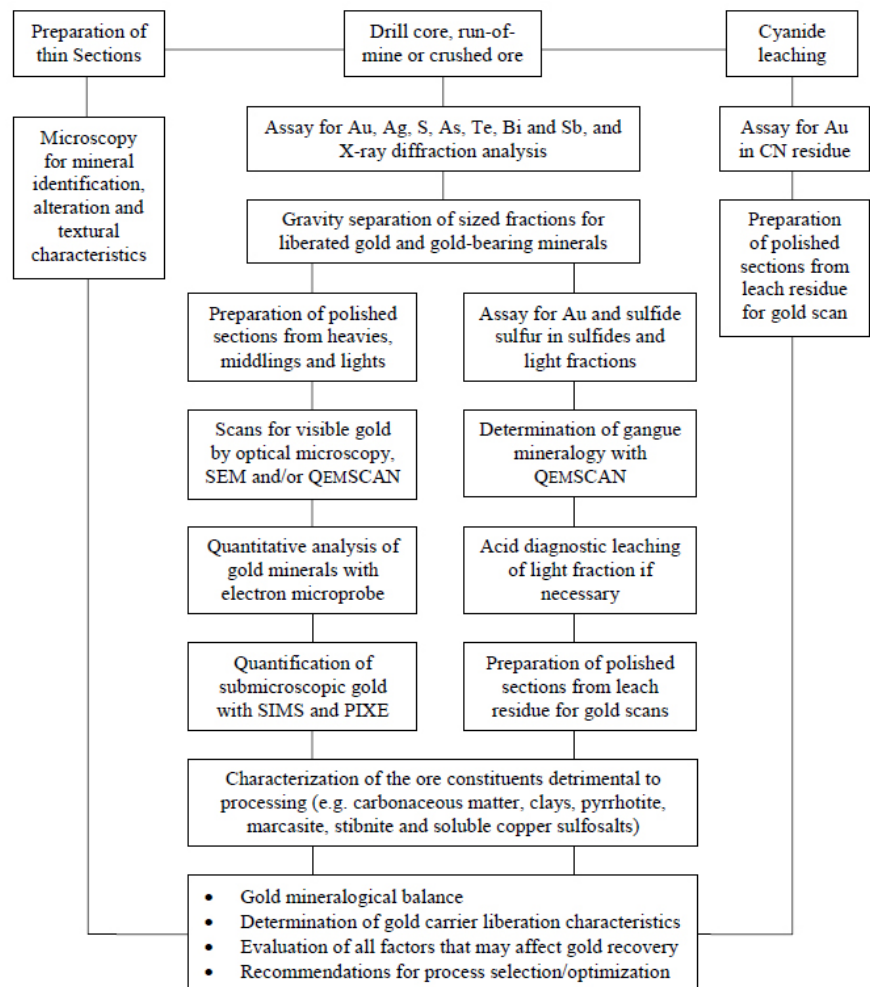

Figure 2: General Investigation Procedure for Gold Studies

SAMPLING AND SAMPLE PREPARATION

Sampling

Sampling is a crucial step in any gold process mineralogy study, particularly when dealing with the ore or concentrate containing coarse gold particles or containing a high content of gold-bearing sulfides. This is because of the inhomogeneous spatial distribution of coarse gold ("nugget" effect) and the higher density of sulfide minerals. Unrepresentative samples will bias the gold assays and mineralogical gold balance. Hallbauer et al. (1972) indicated that irregularity in the gold distribution throughout the Witwatersrand reefs caused gold values to differ by up to four orders of magnitude. The reader is also referred to a paper presented at last years CMP meeting on the subject by Cossio et at (2003). They describe that at La Herradura mine in northern Mexico, ore mineralization occurs in a shear zone with quartz and native gold. The gold size distribution at La Herradura is quite heterogeneous, gold particles being as coarse as 600 μm.

Experience had showed that the existing protocol (using a 50 g sample), established prior to starting up operations, consistently underestimated the gold content in the ore, by about 27%. They devised a new "leaching" protocol, using a 12,000 g sample which, they demonstrated, solved the problem at La Herradura (Cossio, S. et al., 2003). In a study carried out recently by the authors showed that the content of pyrite (assaying 40 g/t Au) between sub-samples split by different methods from a concentrate for mineralogical study and for metallurgical testing was up to 50%. This made the results acquired from both studies incomparable. Therefore, in order to avoid any problems in subsequent studies, a standard sampling procedure must be followed strictly throughout the study, and each sample should be split and assayed carefully. If the mineralogical and metallurgical studies are to be conducted on the same sample, sub-samples should be riffled out at the same time from the same as-received sample using same sampling technique. The high-grade samples, the samples containing coarse gold and the samples containing high content of gold-bearing sulfides should be large enough

to eliminate the "nugget" effect and other sampling problems.

Pre-concentration

Even with properly sampled material, the mineralogist faces significant problems in studying gold ores, owing to statistics and the risk of bias in sample preparation:

• Statistics. The grade of gold in gold ores and mill products is usually low, some tailings retreatment operations having grades below 1 g/t Au (Fleming, 1998). As a result, the chance of readily finding gold minerals within a few polished sections made directly from the head or tailing sample is limited. On average, in a polished section of standard size (25 mm in diameter) made from a sample containing 1 g/t Au, only one 5 μm gold grain is observed. Where the gold occurs as gold telluride such as calaverite or petzite, or as aurostibite, identification can be even more difficult. Consequently, for low-grade ores, it is slow and prohibitively expensive to study sufficient polished sections to adequately address the potential for statistical error.

• Section Preparation Bias. During a gold process mineralogical study, the amount of liberated, attached and locked gold in a sample is normally calculated based on the ratios of surface areas measured under microscope by a mineralogist, or determined by image analysis for liberated, attached and locked gold minerals. The amount of total visible gold is calculated based on the total surface area of gold, content of Au in gold minerals, total mineral coverage, average specific gravity and the weights of material used for polished sections. Although the classical mineralogical approach, when used in isolation, this approach is fraught with risk:

  • When a polished section is made, high SG liberated gold particles preferentially sink to the bottom of the grain section and become exposed when the section is polished. Gold inclusions in lower SG host minerals will have less of a tendency to sink. This introduces bias to the sample, and a risk of over-estimation of the proportion of liberated gold.

• On the other hand, it is difficult to obtain representative polished sections, particularly where coarse gold is present. For example, Henley (1989) noticed the discrepancy between observed and measured Au content in size fractions of ground ore from the Warrego mine, Tennant Creek, based on microscopic scanning of polished sections and Au analysis contents. Observed Au content only accounted for ~69% of the Au assay. These discrepancies are marked even at the high Au contents present in the Warrego fractions; the problem is exacerbated when Au contents are lower and one or two grains of native gold occur in a polished section.

The use of gravity techniques to pre-concentrate the liberated gold overcomes the problem. At SGS Lakefield Research, liberated gold minerals are pre-concentrated by heavy liquid separation, with a superpanner used to clean the Sink fraction. After removing a small amount of highly concentrated "tip" (which contains all liberated gold particles), a "clean" sulfide fraction and silicate fraction will be obtained and assayed for Au (see next section for more details). The amount of liberated gold can be calculated by "subtracting" gold in the sulfide and silicate fractions from the head assay. In this case, a polished section is made for gold scanning, to determine the gold mineral species, size distribution, and for quantitative analysis by the electron microprobe. It can also be assayed for Au when the gold scan is finished. At the same time, polished sections are prepared from sulfide and silicate fractions for gold scan to characterise the contained gold. Work completed by the authors showed that the total amount of liberated gold and attached gold (both directly cyanide leachable) determined by this method is much closer to the gold recovery by cyanide leaching.

The importance of conducting gravity concentration in mineralogical studies is shown in a couple of case studies described below:

CASE STUDY 1:

A bioleach study was initiated at SGS Lakefield Resarch on a sulfide ore assaying 65 g/t Au based on the preliminary mineralogical examination which only identified gold particles locked in arsenopyrite and gangue. To support the bioleaching campaign, a detailed process mineralogy study involving preconcentration and systematic gold scanning was conducted on the ore that was being bioleached. The detailed study showed that about 90% gold had been liberated in a -65 mesh grind and only a small amount of gold was associated with arsenopyrite and scorodite, indicating a totally different process selection (gravity and/or direct cyanidation). Not surprisingly, bioleaching proved not to be the best option.

CASE STUDY 2:

It is well known that gold in the Carlin-type deposits occurs mainly as submicroscopic gold in disseminated sulfide minerals such as pyrite and arsenopyrite. In the study of Carlin-type ores, gravity pre-concentration is also important and is often used to confirm the presence or absence of visible gold, and to concentrate gold-bearing sulfides for gold assay or instrumental analysis. In a study of gold in a high-grade refractory sulfide ore, the head sample (~30 g/t Au) was separated by heavy liquids, and polished sections were made from both heavy and light fractions for gold scanning. Only a few tiny gold inclusions measuring 1-2 μm were observed. Based on the pre-concentration gold and sulphide balance, microscopic observation and pyrite morphology, the mineralogist was able to conclude that the majority of gold likely occurred in submicroscopic form in pyrite, which is not recoverable by direct cyanidation. Subsequently, SIMS analysis and cyanide leaching were conducted on the ore. The SIMS results showed that over 85% of gold was locked in pyrite as solid solution gold, and the cyanide leaching test showed that only less than 15% gold was recoverable.

Polishing

Polishing is another important step in sample preparation. Gold minerals are softer than any other associated minerals, which makes careful grinding and polishing of grain sections critical to successful gold studies. Grain sections (sometimes blocks) need to be well polished so the gold scan and mineral identification can be conducted at high speed and with good quality, particularly when the gold scan is conducted by automated digital image system (ADIS). At the same time, extra care should be given to the grinding and polishing to ensure that no gold particles will be polished away. Polished sections should never be over-ground and/or over- polished. This is particularly important in the preparation of the sections containing fine gold particles.

Gold samples (particularly low-grade tailing samples) are very sensitive to contamination. This requires that the whole sample preparation process be conducted in an enclosed area, which is dedicated to gold mineralogical sample preparation. All equipment and tools, such as riffle, screens, beakers, pans, spatulas and brushes, must be cleaned thoroughly after each use. In addition, extra care should be given to the high-grade samples. When working on a suite of samples, always start from low-grade samples to high-grade samples to minimise risk of cross- contamination.

ANALYSIS

Table 4 lists some techniques used in gold process mineralogical analysis, which can be classified into two categories: conventional (1-6) and advanced instrumental (7-14) techniques. The application of each technique is discussed below.

Fire Assay

Fire assaying is the traditional method of gold analysis and can measure gold concentrations from 0.001 to >50 g/t.

In gold process mineralogy, fire assaying is an integral element in many parts of a typical study, as it provides bulk gold balance information, complimenting the mineralogical information obtained from the other techniques. For low-grade samples, duplicate or triplicate gold assays are recommended in order to evaluate the variation between the assays. In this case, an average Au assay is used in the mineralogical balance calculation.

Non-gold assays may also be used by the mineralogist to predict the possible occurrence of gold in the sample being studied at the beginning of the project. If the Ag concentration is very low, it may imply that gold occurs as native gold. Low concentration of Au and high concentration of Ag may indicate the presence of electrum and/or kustelite.

Cyanide Leaching

Cyanide leaching is often used for determining the maximum amount of recoverable gold by cyanidation which, mineralogically, represents the fraction of exposed gold. Another application of cyanide leaching in gold process mineralogy is to provide independent confirmation, by difference, of the submicroscopic gold content acquired by SIMS or other technique. In this case, intensive cyanide leaching will be conducted on a finely ground

sample (-5 μm) at a high cyanide concentration level (5 g/L NaCN) for 48h or 72h to remove all the exposed gold and the leach residue will be assayed for Au. Submicroscopic gold content acquired by SIMS should be equal or close to the gold content in cyanide leach residue.

NO.	TECHNIQUE	ABBREVIATION	DETECTION LIMIT	APPLICATION
1	Fire Assay	FA	0.1-50 g/t Au	Determination of gold in all forms
2	Quadruple Ton One 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	(~0.2-0.5 um)	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	QEMSCAN	-	Gold scan, mineral identification, iberation and surface morphological study
10	Electron Probe Microanalysis	EPMA	0.1% EDX 0.02% WDX	Compositional analysis of gold and other minerals
11	Dynamic Secondary Ion Mass Spectrometry	D-SIMS	ppm	Quantification and mapping of gold in sulfides and FeOx
12	Proton-induced X-ray Emission	u-PIXE	ppm	Quantification and mapping of gold in sulfides and silicates
13	Laser Ablation Microprobe Inductively Coupled Plasma Mass Spectroscopy	LAM-ICP-MS	ppm-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

Gravity Concentration

The most commonly used gravity concentration techniques in process mineralogy are heavy liquid separation (HLS), superpanning and the Mozley table. Wilfley tables and Knelson concentrators are also used when a large sample is treated. HLS is often used as a preconcentration technique. At SGS Lakefield Research, HLS is conducted in a centrifuge using a small aliquot of 10-20g material, depending on the size fraction. A specific gravity of 2.95 is often used to separate opaque minerals (sulfides, oxides and other heavy minerals) and nonopaque minerals (silicates, carbonates and carbonaceous matter etc.). With careful and delicate preparation and operation, heavy liquid separation at SGS Lakefield Research is successful on fractions down to -5μm.

After heavy liquid separation, the sink fraction is panned on a superpanner to further concentrate gold minerals and gold-bearing sulfides. By using a superpanner, a small amount of tip (i.e. pan concentrate, usually 100-500mg), is obtained for gold examination. Usually, all liberated gold mineral particles are concentrated into the tip, and a "clean" sulfide fraction and silicate fraction obtained for gold assays (Figure 3). The proportions of liberated gold, gold associated with sulfides and gold associated with silicates are estimated based on the available gold assays and mass balance. Polished sections are prepared from pan concentrate, sulfide and silicate fractions for gold scan. Another advantage of using a superpanner is that gold and other mineral particles of interest can be easily picked out from "tip" for morphological study and surface characterization.
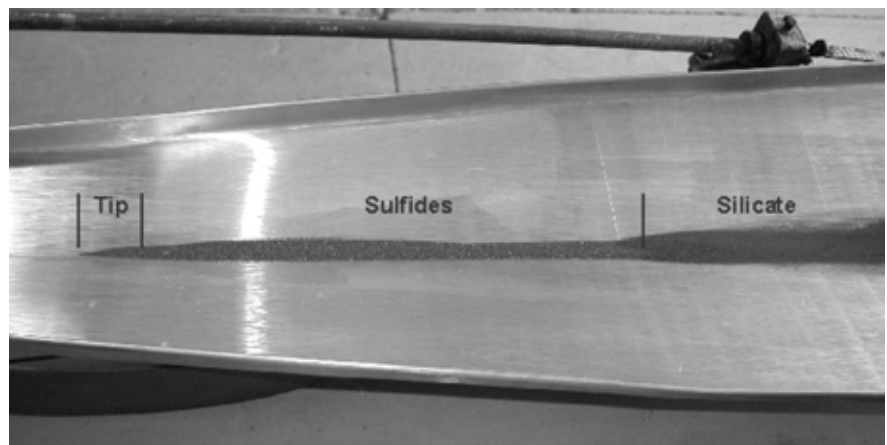

Figure 3: A photograph showing the separation of a sulfide ore by superpanner. Sulfide fraction and silicate fraction were well separated.

Superpanning has been proven to be an excellent technique in sample preparation for gold mineralogical studies. A recent study was conducted by the authors to test the efficiency of superpanning. In the study, 0.5 g of finely ground galena (25 μm) was added to 20 g of cleaner tail sample containing no lead minerals and then well mixed before panning for 30 minutes. Two tests were done. Test one was panned once, and Test two was panned three times. After each panning, the tip was removed and saved for Pb assay. The superpanner recovered 98% of the galena (and 1% of the remaining material) in one panning. Repeating the process three times raised the recovery to 99.3%, still with negligible recovery of the remaining material (Table 5). Similar work conducted on pre-sized synthetic gold samples showed excellent recoveries down to 10 microns (Thrower, 1995).

In some cases, panning is difficult due to the particle size and shape of gold minerals. Large gold flakes often stay behind the "tip" and are buried within the adjacent sulfide fraction. Therefore, each pan has to be carefully checked by an experienced mineralogist under a stereoscope. The occasional gold particle found outside the "tip" can be moved into the "tip". However, if excessive gold particles are observed behind "tip", the tip must be carefully removed and the rest of material repeatedly panned until no gold is observed in the sulfides fraction. This makes panning time-consuming, but it provides the best separation on gold samples and therefore is highly recommended for gold studies.

TEST #	NO. OF PANNING	PRODUCT	GRADE (% Pb)	WT (g)	UNITS DIST.	DISTRIBUTION
Test 1	Single panning	tip	51.1	0.86	43.95	98.1%
		Middlings	0.67	0.6	0.40	0.9%
		Tails	0.026	18.05	0.47	1.0%
			2.30	19.51	44.82	100.0%
Test 2	Single panning	tip 1	63.6	0.67	42.61	93.5%
		tip 2	21.6	0.11	2.38	5.2%
		tip 3	3.03	0.08	0.24	0.5%
		Middlings	0.07	0.97	0.07	0.1%
		Tails	0.016	17.23	0.28	0.6%
					45.57	100.0%

Acid Diagnostic Leaching

Acid diagnostic leaching has been developed for gold ores to determine the association of gold with different minerals (Tumilty, J.A. et al., 1987; Coetzee, M. et al., 1988; Lorenzen, 1995). This method includes:

- cyanidation and solution gold analysis, as a first step for the determination of free gold; secondly,
- leaching with hydrochloric acid, followed by cyanidation and solution gold analysis, to define gold bound to carbonates, pyrrhotite, galena, goethite; thirdly,
- leaching with sulfuric acid, followed by cyanidation and solution gold analysis, to determine gold associated with uraninite, sphalerite, labile copper sulfates, labile base metal sulfides and labile pyrite; fourth,
- leaching with nitric acid, followed by cyanidation and solution gold analysis, to determine gold associated with pyrite, arsenopyrite and marcasite.
- The residue is leached with hydrofluoric acid, or analyzed by fire assay.

CASE STUDY

Kojonen et al. (1999) conducted a sequential leaching on the +20 μm and -20 μm fractions of three samples from Suurikuusikko gold deposit in Kittilä, western Finnish Lapland. The results of diagnostic leaching tests showed that only a minor portion (4.1%) of the gold was in cyanide leachable form, i.e. free gold. On average, 57% of the gold was liberated by nitric acid, which means that it is bound to pyrite and arsenopyrite as inclusions or as lattice gold. On average, 36% of the gold was left in acid leach residue, representing the gold associated with silicates.

Optical Microscopy

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 500x 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. For an experienced mineralogist, two to three polished sections can be examined per day, depending on the size fraction and the number of gold grains observed. During a gold scan, all gold mineral occurrences should be recorded by grain size, shape, association and location in host minerals (if applicable). It is recommended that the whole surface area of the section be scanned to obtain representative information. If the section contains too many gold particles, the surface can be divided into two or even four parts with one or two part(s) examined. Representative digital photomicrographs are taken to show the occurrence of gold and bulk mineralogy of the sample.

Polished sections should be examined shortly after they are polished if they contain electrum, kustelite and native silver because their rapid oxidation may affect identification. For this reason, an automated image analyzer is not suitable for ore assemblages containing these minerals.

Automated Digital Image System
Gold scanning can be carried out with an automated digital image system (ADIS) fitted to an optical microscope or an automated image analysis coupled with a SEM-EDS system. Image

analysis techniques have been described in detail by Petruk (1989 and 2000) and Lastra et al. (1998). These techniques, if applied properly, can be more productive and provide better quality results than optical methods. Alternatively, a SEM-EDS can be used manually, but it will take a considerably longer time than with the optical microscope, because it is difficult to differentiate gold from other minerals with high backscatter signals such as galena, native silver and native tellurium.

SEM and QEMSCAN
Scanning Electron Microscopy (SEM) gives high quality images of particle textures, such as surface morphology, pore structure, permeability and coatings and is particularly useful when coupled with an energy dispersive

X-ray spectrometer (EDX), in addition to its capability of being used for gold scanning. For example, Wang et al. (1992, 1993) described the use of a SEM for the deportment study of gold in the Jinya Carlin-type gold deposit in China. They found that a minor amount of gold in the Jinya ore occurred as fine-grained (in micron size) gold particles on the surface of pyrite and arsenopyrite. This represented the fraction of cyanide recoverable gold.

QEMSCAN (Quantitative Evaluation of Material by Scanning Electron Microscopy) acquires quantitative mineralogical data automatically. At SGS Lakefield Research, the LEO 440 scanning electron microscope platform is equipped with four light element energy dispersive X-ray detectors and an X-ray microanalyser. Raw data is processed using proprietary software designed by CSIRO and presented in a variety of tabular and graphical formats. QEMSCAN provides quantitative data regarding gold grain size distribution, gold mineral composition, mineral association and locking characteristics. It is used in gold process mineralogy to develop and optimise processing strategies and for surface morphological study of gold and gold-bearing minerals.

Electron Probe Microanalysis
Electron Probe Microanalysis (EPMA) was first introduced into the geological science in the 1960's. Soon afterward, it was used to investigate gold ores (Jones et al., 1968) and initial applications examined the possibility of automated searching for gold grains in samples of low concentration. The most important application of EPMA in gold mineralogy is its quantitative analytical capability. In the 1970's and 1980's, EPMA was the only electronic technique that could analyze submicroscopic gold particles in sulfides from refractory gold ores. Now, it is rarely used in this mode due to its relatively high detection limits (0.1% in EDS mode and 0.02% in WDX mode) compared to the concentration of gold in refractory sulphide ores. A secondary yet important application is the generation of X-ray maps to illustrate distribution of Au, Ag and other elements in single particles of gold that are compositional zoned.

In routine process mineralogical studies, a minimum of 10-20 electron microprobe analyses per sample are required to validate the composition of gold and to ensure that reasonably accurate gold balances can be calculated. Higher numbers of analyses are required if the composition data show significant variation (>5%).

SIMS
Secondary ion mass spectrometry (SIMS) is one of a few most important microbeam techniques applied in gold studies because of its unique quantification and mapping capabilities. Theoretically, it can detect and measure all the elements in the periodic table in concentration from ~1% to 10 ppb and has the ability to discriminate between the isotopes of many elements. The element and isotope contents can be measured with a sensitivity that is as high as the sensitivity of bulk analysis methods, such as atomic absorption (McMahon et al., 1998). Its exceptional operational capabilities include (1) small beam size: ~20 μm; (2) low detection limit for Au (0.3 - 0.5 ppm); (3) shallow beam sampling depth (0.5 - 1μm); (4) individual particle analysis; (5) depth concentration profiling and (6) element mapping capabilities. These positive attributes are balanced by a destructive analytical mode in contrast to electron microprobe analysis.

High sensitivity makes SIMS an excellent analytical tool for the quantification of trace elements in a variety of materials. Presently, it is probably the best technique for the quantitative determination of submicroscopic gold in sulfides. The SIMS in-depth concentration profiling is used to discriminate colloidal gold and solid solution gold. Colloidal gold (0.02-0.1 μm) can be identified from the "spikes" and "bumps" in the in-depth concentration profiles of gold, whereas solid solution gold is characterized by "flat" in-depth profiles (Figure 12). SIMS mapping is used to show the location and distribution of submicroscopic gold in host minerals.

For determination of submicroscopic gold in sulfides by SIMS, 20-30 analyses are needed for each potentially gold-

bearing species.

Sample preparation and particle selection are very important steps in a SIMS study. As a first step, the mineralogist studies the sample under an optical microscope, and the number of particles of each gold carrier and each morphological type is determined. Although it is well known that pyrite is the most common and most important gold carrier, all types of pyrite do not always contain appreciable amounts of gold. Thus, the particles inventory must include all morphological types although experience may focus the mineralogist on one or two major gold-carrier morphological type(s). To this end, the mineralogist should work closely with the SIMS operator to ensure that the study is properly focused. Intensive cyanidation of finely ground "clean" sulfide concentrate and related analysis of the leach residue for gold provide an independent check on the quality of the gold deportment calculated using SIMS data. Any gold left in the leach residue can be regarded as submicroscopic gold and the gold concentration acquired by SIMS should be equal or close to this value. An example of SIMS analysis and data interpretation is given later in this paper.

PIXE
Proton-induced X-ray emission (PIXE) is a microbeam analytical technique that can be used for quantitative analysis of a wide range of elements in selected mineral particles, either in polished blocks or in grain mounts.

PIXE is a multi-element and non-destructive analytical technique. Its principal benefits include:
1.   Analysis of individual opaque or non-opaque mineral particles,
2.   Small beam size (~5 μm),
3.   Quantification of trace elements (MDL for Au: ppm) and (4) Two-dimensional X-ray mapping for element distribution.

Cabri et al. (1985) and Cabri (1988) discussed the applications of PIXE in ore deposit mineralogy and metallurgy illustrating their case with trace element data obtained from sulfides in a variety of massive-sulfide ore deposit types. Cabri et al. (1998) reported that low ppm detection limits could be obtained in most cases for elements that range from Fe to U.

LAM-ICP-MS
LAM-ICP-MS (Laser Ablation Microprobe Inductively Coupled Plasma Mass Spectroscopy) is an emerging technique for mineralogical and geochemical studies. It offers enormous potential in trace element analysis through significantly improved detection limits for in-situ analysis, and the ability to generate profiles through minerals by progressive ablation. The system is capable of determining, with good accuracy, a large suite of trace elements in various mineral hosts including silicates, carbonates, phosphates, oxides, and sulfides. Limits of detection vary from a few ppm to a few ppb depending upon a number of operating variables, such as pit size and number of elements determined. Sampling resolution better than 10 μm can be achieved, although ablation pits on the order of 40 μm are usually used, when grain size allows, to provide better precision and detection limits. LAM was designed primarily for in-situ analysis of minerals in petrographic sections (thin sections and grain mounts).

Hinchey et al. (2003) used LAM-ICP-MS to determine whether Au is distributed homogeneously in sulfides, particularly arsenopyrite, or is contained as micronuggets in the Lodestar prospect in eastern Newfoundland. The results demonstrated that the Lodestar arsenopyrite contains Au concentrations up to 201 g/t and that it was "homogeneously" distributed (i.e., no nugget effect) and contained within the structure of arsenopyrite. Other sulfides, such as pyrite and chalcopyrite, contained very low Au concentrations.

TOF-LIMS
Time-of-Flight Laser Ion Mass Spectrometry (TOF-LIMS) is used in gold mineralogy for the quantification of gold adsorbed on the surface of carbonaceous matter and other minerals and for the determination of inorganic surface composition. Using this technique, it is possible to analyze, in a few minutes several spots on the surface of a single surface gold carrier or a single gold particle 20 μm or less in diameter with a sampling depth of 0.01-0.05 μm.

Chryssoulis et al. (2003) conducted a comparative study by TOF-LIMS on the floated and rejected free gold grains from a number of commercial benefication plants and from pilot plant testwork. The study showed that the faster floating gold grains always have more surface silver, implying that silver may have assisted gold flotation as an activator.

Other Techniques
Other techniques that have been used or have potential application in gold mineralogy (mostly for academic research) include transmitted electron microscopy (TEM), Auger emission spectrometry (AES), X-ray photoelectron spectrometry (XPS), Mossbauer spectroscopy and Sychrotron radiation. Detailed information about these techniques is beyond the scope of this paper.

CASE STUDIES OF GOLD DEPORTMENT

Case Study 1: Deportment of gold in a mildly refractory flotation concentrate and concentrate CN tails

The flotation concentrate was composed mainly of silicates and pyrite, with trace amount of gold (30 g/t). Gold occurred as liberated, gold attachments to and inclusions in pyrite, and inclusions in silicates. Gold tellurides were negligible. The concentrate sample was preconcentrated by heavy liquid separation at 3.1 g/cc followed by superpanning. A small amount of tip, a clean sulfide fraction and a clean silicate fraction were obtained. A polished section was prepared from tip, and two were prepared from each of sulfides and silicates for gold scanning. Sulfide and silicate fractions were assayed for Au. The study showed that 65% of gold

was liberated, 31% was associated with pyrite (as attachments and inclusions) and 4% was associated with silicate (as inclusions). Cyanide leaching was conducted on the concentrate and yielded a 75% gold recovery. Detailed gold deportment study was conducted on CN tails, indicating that 80% of the gold in the leach residue was carried by pyrite as inclusions (accounting for 21% of gold in concentrate), indicating that gold attached to pyrite accounted for ~10% of the head assay. No liberated gold or gold attachments to pyrite were observed in the leach residue, showing that the cyanide recoverable gold was leached effectively. It was concluded that gold in the flotation concentrate occurred as liberated gold (accounting for 65%), gold attached to pyrite (accounting for 10%), gold locked in pyrite (21%) and gold locked in silicates (4%).

Studies also indicated that all the gold associated with pyrite is fine-grained, with attached gold ranging from 1 to 40 μm and locked gold from <0.5 to 28 μm (Figure 4). Attachment to pyrite is not a problem for gold recovery by cyanidation, because all the attached gold had been leached during the original cyanide leaching. Recovery of gold locked in pyrite needs finer grinding.

To determine the regrinding fineness, all of the gold-bearing pyrite particles were measured and the grain size plotted (Figures 5 and 6). Figure 5 shows the size and surface area distribution of attached gold versus pyrite grain size, indicating that over 77% of the gold particles and over 90% of the surface area were associated with pyrite particles below 100 μm. Figure 6 shows the size and surface area distribution of locked gold versus pyrite grain size, indicating that ~76% of the gold particles and surface area were associated with pyrite particles over 100 μm. Figure 6 also shows that ~50% of the gold particles and ~65% of the

surface area were locked in pyrite ranging from 100 to 150 μm. These results indicate that ~75% recovery of locked gold can be expected by grinding the pyrite concentrate to below 100 μm.
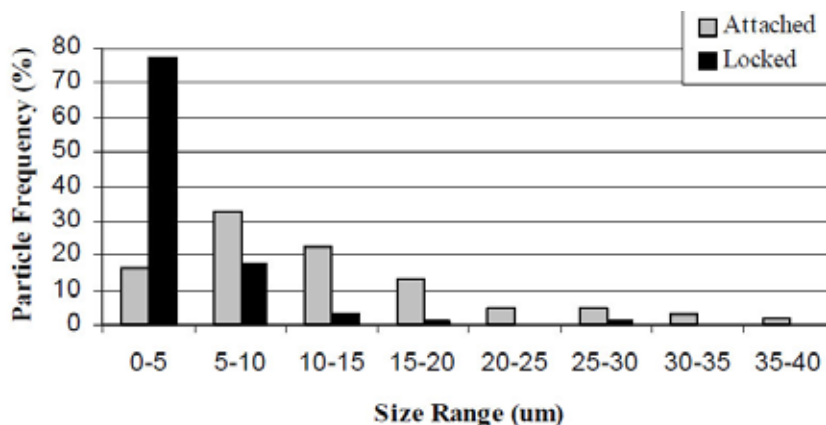

Figure 4: Size distribution of gold in a flotation concentrate leach residue.
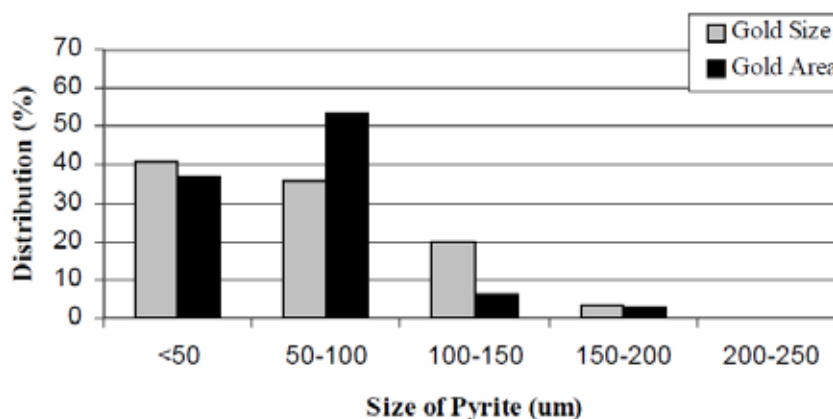

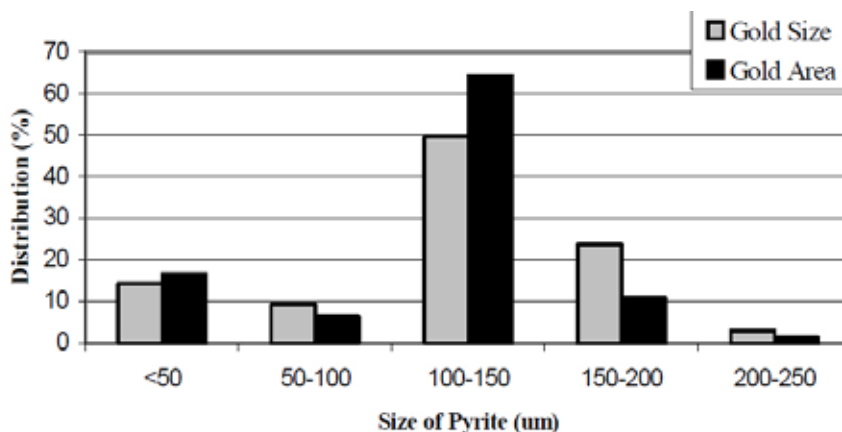Figure 5: Size distribution of attached vs. size of gold-bearing pyrite.

Figure 6: Size distribution of locked vs. size of gold-bearing pyrite.

Case Study 2: Deportment of gold in a highly refractory Carlin-type gold ore

In the Jinya Carlin-type gold deposit in Guangxi, China (Wang et al, 1994), the pyrite-arsenopyrite ore contains ~6 g/t Au. Dominant sulfide species include pyrite (7.7%), arsenopyrite (2.5%) and realgar (1.4%). The ore is characterized by its extremely low gold recovery (5-6%). A detailed study on the gold deportment was conducted using a comprehensive integrated approach, which involves optical microscopy and several advanced microbeam techniques such as SEM, EPMA, PIXE and SIMS. The deportment of gold was determined as follows:

1. Microscopic gold, which was cyanidable, accounted for 6% of the head assay. SEM studies (Figure 7) confirmed that this part of the gold occurred mainly as micron-size gold particles.
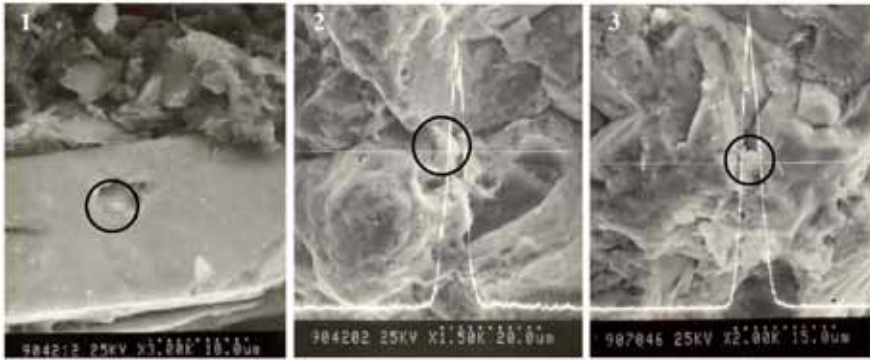
Figure 7: 1500x-300x, SEM BSE images showing three fine-grained gold particles (inside balck circle): 1-gold (1x2 µm) on arsenopyrite; 2-gold (4x8 µm) on pyrite; 3-gold (3x3 µm) on pyrite.
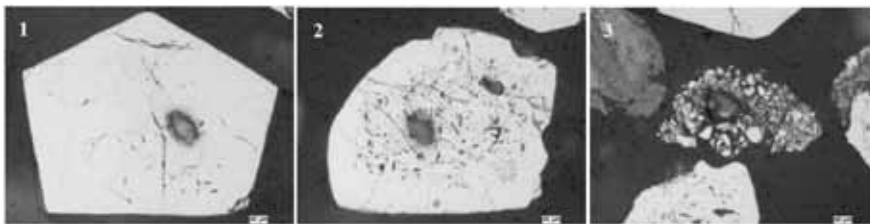

Figure 8: 500x, reflected light photomicrographs showing three morphological types of pyrite: 1 - coarse (0.51 ppm Au); 2 - porous/blastic (5.6 ppm Au); and 3 - fine-grained (72.4 ppm).
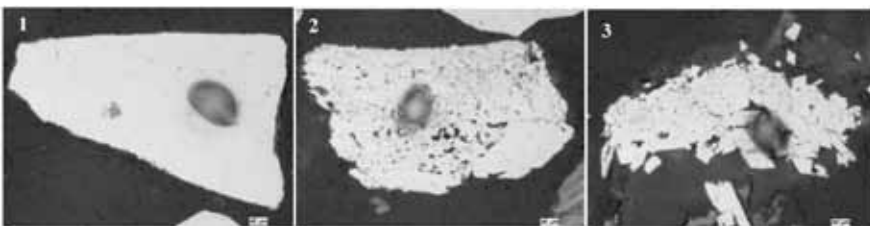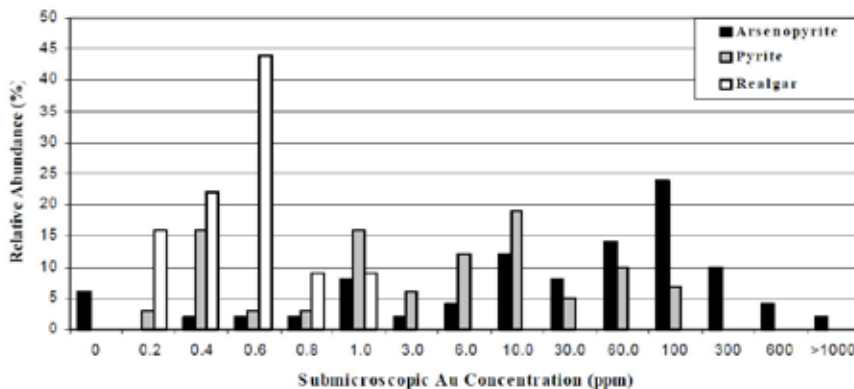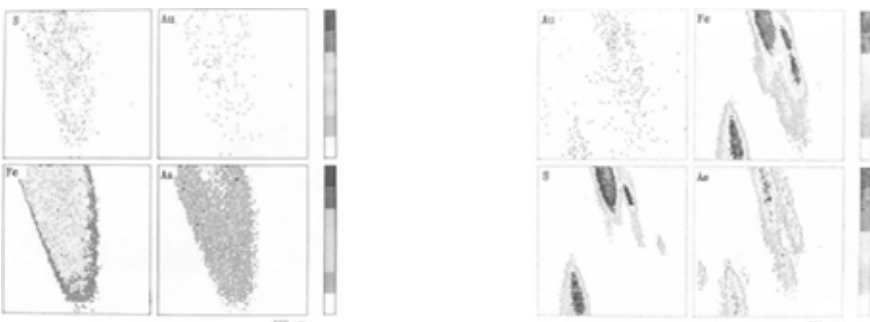

Figure 9: 500x, reflected light photomicrographs showing three morphological types of arsenopyrite: 1 - coarse (17.6 ppm Au); 2 - porous/blastic (173.1 ppm Au); and 3 - fine-grained (545 ppm).

Figure 10: Gold concentration in arsenopyrite (avg. 195 ppm), pyrite (avg. 13.2 ppm) and realgar (avg. 0.68 ppm) from the Jinya ore.

2. SIMS quantitative analysis indicated that arsenopyrite and pyrite were the two major carriers of submicroscopic gold, carrying 77% and 16% of gold, respectively. Gold preferentially concentrated in the fine-grained varieties of arsenopyrite and pyrite (Figures 8, 9 & 10) which made this ore grind-sensitive with an expected positive correlation between the recovery of gold-rich sulfides and gold recovery.

3. PIXE mapping showed that the distribution of gold in the Jinya ore is closely associated with sulfide minerals and distributed homogeneously in pyrite and arsenopyrite (Figure 11).

4. Smooth concentration profiles obtained by SIMS in-depth concentration profiling (Figure 12) indicated that gold in arsenopyrite and pyrite occurred as solid solution gold, which explains why the gold recovery by original cyanide leaching was extremely low.

As a result of this investigation, a gold recovery of over 90% was achieved through a combination of floating the gold-bearing sulfides followed by leaching the roasted flotation concentrate.

SUMMARY

Process mineralogy can play an important role in optimizing the metallurgical processing of gold ores. It is widely used to characterize gold in gold ores and mill products, and to determine the mineralogical problem(s) causing gold losses. The information acquired from a process mineralogical study can be used as a basis for a metallurgical testwork program for process design or optimization. Ideally, a process mineralogical study should be conducted prior to the start or at the early stage of a metallurgical testwork program or as a trouble- shooting tool whenever it is needed.

Figure 11: PIXE mapping of Au, Fe, S and As in pyrite (left) and arsenopyrite (right). Au occurred only in these sulfide minerals and showed a positive correlation with S and As.
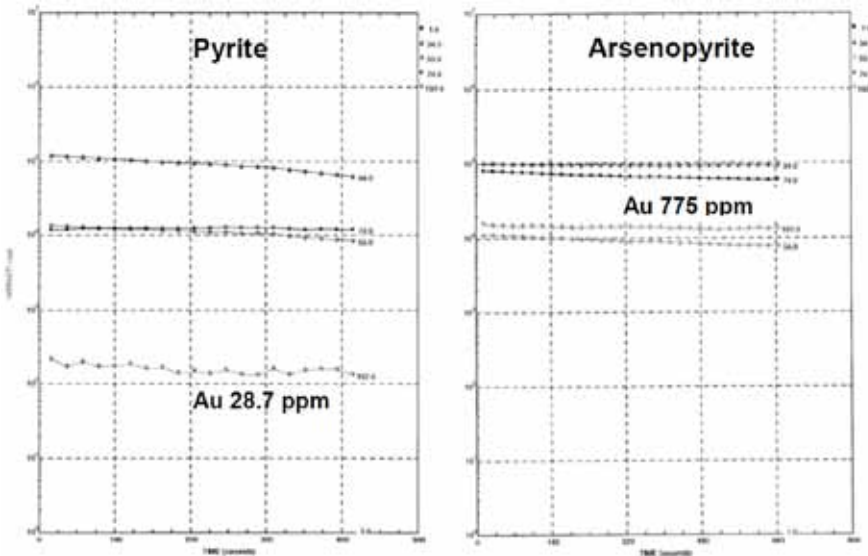
Figure 12: SIMS in-depth concentration profiles of gold in pyrite (left) and arsenopyrite (right).

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