MODERN GOLD DEPORTMENT AND ITS APPLICATION TO INDUSTRY

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ABSTRACT

Modern gold deportment studies include physical, chemical and mineralogical assessments, combined to obtain a full understanding of the nature and variability of gold in a resource. The objective is to provide information which will allow cost effective and practical processing by informing decisions regarding resource evaluation, mining method and extraction process optimization.

The distribution of gold, based on speciation, grain size and mode of occurrence (liberation, exposure, and mineral association) is quantitatively determined by means of automated Scanning Electron Microscopic Techniques (QEMSCAN/MLA). Furthermore, general mineralogical characterization is undertaken in order to characterize the gangue components; with special emphasis on deleterious characteristics of the ore (e.g. cyanide consumers such as secondary Cu-species, preg-robbers/borrowers, passivation due to Sb-minerals or As-minerals and oxygen consumers such as pyrrhotite/marcasite).

Predictions based on the mineralogical observations are confirmed by physical and chemical testwork. These include grading analyses, gravity separation, direct cyanidation, and diagnostic (sequential) leach tests.

1. INTRODUCTION

The most efficient gold extraction processing route is directly related to the inherent mineralogical features of the gold ore being processed. The mineral assemblage determines the performance of all chemical and physical processes involved in gold extraction (e.g. Chryssoulis and Cabri, 1990; Marsden and House, 1992; Chryssoulis and McMullen, 2005). It is therefore crucial to accurately characterize the mineralogical nature of the ore to be processed; i.e. characterization of the precious metal phases (gold deportment) and gangue minerals. In the past, mineralogical testwork was often time-consuming, relatively expensive and the data obtained was qualitative rather than quantitative. Advances in automated mineralogy, by Scanning Electron Microscopy, revolutionized this field of study as the data became comprehensive and quantitative. Various examples of the use of automated analysis systems for gold deportment studies are found in the literature (e.g. Gottlieb et al., 2000; Butcher et al., 2000; Chryssoulis, 2001; Gu, 2003; Goodall et al., 2005; Goodall, 2008). It is therefore inexcusable for mineralogical factors to be overlooked by project metallurgists, resulting in unnecessary testwork, non-optimum processing flowsheets and decreased profitability.

The main aim of a gold deportment analysis is to locate and describe gold-containing particles in order to determine the gold speciation, grain size and mode of occurrence (gold liberation, exposure, and mineral associations) as well as to generally characterize the mineralogical composition of the ore. Two common problems affecting the results of a gold deportment study are representivity of the samples being analysed and variation in gold grade. Two main factors influence representivity namely (i) biased sample collection and (ii) the "nugget effect" caused by sparse and inconsistently distributed gold grains. Since a gold deportment study is based on a reasonable, but statistical number of observed gold grains (not always possible in very low grade material), the number of polished sections prepared for examination will depend on the grade of the sample. Variation in gold grade may result in difficulty in determining an adequate number of polished sections to prepare for examination. Thus reliable results are achieved by proper sample selection, sufficient sample mass, careful splitting, adequate number of replicate polished sections and proper data validation. The mineralogical data is validated by supporting chemical and metallurgical data (including gold mass-balances).

A wide range of metallurgical techniques are used to test the extractability of gold from gold ore. The most common metallurgical tests employed are direct cyanidation, gravity separation and diagnostic leaching. Diagnostic leaching is a procedure that involves the selective destruction of minerals, followed by a cyanide leach step to recover the newly exposed gold after each destruction stage. Various examples and adaptations of the application of diagnostic cyanide leach tests are found in the literature (e.g. Lorenzen and Tumilty, 1992; Lorenzen, 1995; Marsden and House, 1992; Henley et al., 2001; Goodall et al., 2005; Celep et al., 2009). The results of diagnostic leach tests are sometimes difficult to interpret and often misleading, especially if additional mineralogical data is not available.

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It is found that a combination of mineralogical and metallurgical tests provides the most cost- and time-efficient means to fully characterise gold-bearing samples. The data is used to predict the behaviour of the ore during processing and to recommend a cost effective processing route.

This paper describes the methodology employed by the MetMin Section at SGS South Africa. A case study is discussed to demonstrate the applicability of the methodology. Generic reference is made to results obtained from other gold ore projects completed at SGS South Africa, during the last few years. SGS South Africa uses QEMSCAN[1] technology as an electron microscopic mineralogical tool, but an MLA[2] will give similar results. A full review of the QEMSCAN methodology has been provided by Gottlieb et al. (2000).

2. METHODOLOGY

Mineralogical characterization and gold deportment studies must be done on representative samples of the different or variable domains or zones within the ore body. The domains within an orebody are normally defined during the earlier stages of exploration. The domains are based on grade, lithology and mineralogical composition, degree of weathering or alteration and spatial distribution. Composite samples of each of the different domains usually comprise drill core, but could also be drill chips, coarse rejects from assayed samples or even bulk rock samples. A composite sample mass of about 10–50 kg is used for a full gold deportment study.

A full gold deportment study includes:

a. Crushing and milling to achieve the required particle size distribution.

b. Head chemical analysis and gold assays.

c. Modal mineralogy.

d. Grading analysis.

e. Heavy liquid separation analysis.

f. Gravity separation analysis.

g. Gold deportment of particulate gold in the head sample and/or gravity concentrate and/or heavy liquid separation (HLS) sinks fraction.

h. Direct cyanidation of the head sample.

i. Diagnostic leach analysis of the head sample and/or gravity tailings.

Gold deportment testwork options are illustrated in Fig. 1. A full gold deportment study may not always be done on the head material, due to grade, time and cost constraints. A "Modified Gold Deportment" is then performed on a concentrate, where the gold grains are pre-concentrated by gravity separation. This has similarities to the method described by Lastra et al. (2005), where the gold concentrated by hydroseparator is described. The concentrate only represents a certain proportion of the total gold in the sample, and therefore, a diagnostic leach test is done on the gravity tailings in order to obtain a full picture of the gold deportment.

2.1 CRUSHING AND MILLING

Most gold ores should be milled to at least 50–80% passing 75 μm for effective gold exposure (Marsden and House, 1992). Therefore, at least 10 kg of each representative composite sample is milled to 50% passing 75 μm for the initial testwork (grading, heavy liquid separation and/or gravity separation). A split aliquot of 1 kg is milled to 80% passing 75 μm for head chemical analyses (including gold assays), mineralogical characterization, gold deportment and cyanidation testwork. If it is known that the ore contains very fine-grained gold, then finer grinding down to 80% passing 53 μm may be required.

2.2. HEAD ASSAYS AND CHEMISTRY

Split aliquots of each composite sample (50% passing 75 μm) are analysed by X-ray Fluorescence (XRF) for major elements, by Leco for total S and organic C, and by Inductively Coupled Plasma Spectroscopy (ICP-OES/MS) for specific trace elements (Cu, Ni, Pb, Zn, Sb, Te, Hg, and Bi). The arsenic and silver grades are determined by Atomic Absorption Spectroscopy (AAS). Multiple gold analyses are done by fire assay AAS finish (30 g split aliquots).

2.3. GRADING ANALYSIS

A split aliquot of 500 g to 1 kg of each sample (50% passing 75 μm) is screened into six size fractions, and each fraction is assayed for its gold and sulphur content. The 212 μm, 106 μm, 75 μm, 53 μm, and 25 μm screens normally give a good indication of the gold-by-size distribution, but different size intervals may be used if very coarse or very fine gold is suspected. The grading analysis gives an indication of the gold grain association with predominantly coarse-grained or fine-grained particles. If a large proportion of the gold reports to the coarse fractions, then there is a strong possibility that the ore contains coarse gold. Some ores display a bi-modal distribution, indicating the possible presence of both fine-grained and coarse-grained gold. In tailings samples, however, grading analyses may sometimes be misleading as gold reporting to the coarse fractions is often fine-grained and locked in coarse gangue particles.

2.4. HEAVY LIQUID SEPARATION

Gold may be upgraded by means of heavy liquid separation (HLS). HLS analysis is conducted on a 500 g to 1 kg sub-sample (050% passing 75 μm), deslimed at 25 μm, using TBE @ 2.96 SG. The distributions of gold and sulphur across the slimes-, floats- and sinks fractions are determined. The result of the HLS gives an indication of the amenability of the ore to gravity recovery. However, since the sample must be deslimed for HLS to be effective, a certain proportion of the gold that would be amenable to gravity separation (grains >10 μm in size) might report to the slimes fraction and not to the HLS sinks.

Gold reporting to the floats fraction is usually fine-grained and associated with light gangue, such as silicates and carbon. Entrainment of liberated gold grains is not

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[1] *Quantitative evaluation of minerals by scanning electron microscopy.*

[2] *Mineral liberation analyzer.*

uncommon, especially for very fine-grained samples. Gold reporting to the sinks fraction is mostly liberated and larger than 25 μm in size or associated with heavy gangue minerals like oxides and sulphides, larger than 25 μm in size.

2.5. GRAVITY CONCENTRATION

In order to achieve a mass pull of 2.5–3%, two split aliquots of 4 kg from each composite sample (50% passing 75 μm) are processed by means of Falcon or Knelson concentrator to produce two gravity concentrates and gravity tails. The two gravity concentrates are combined as are the two tails. The gravity tails are assayed for their gold content and the gold distribution is calculated. Polished sections are prepared from the gravity concentrate and these sections are examined by means of optical microscopy and electron microscopy in order to establish the gold deportment of the particulate gold reporting to the concentrate fraction. Gold recoveries greater than 40% strongly suggest that gravity separation should be part of the processing route.

2.6. MINERALOGICAL COMPOSITION

X-ray Diffraction (XRD), optical microscopy and QEMSCAN Bulk Modal Analysis (BMA) are employed to obtain the detailed quantitative mineralogical composition of each sample. Concentrations of minerals detrimental to processing, such as pyrrhotite which is an oxygen consumer, are obtained.

XRD analysis is done in order to identify the major minerals present. Data collection is done using an X-ray diffractometer employing Co-radiation, since most gold ores are iron-rich and this causes X-ray fluorescence (resulting in a high background) when Cu-radiation is used. XRD is a quick and inexpensive way to identify and/ or quantify minerals, particularly those not easily distinguishable by other techniques, e.g. identification of clay minerals and detrimental phyllosilicates, like pyrophyllite and talc.

QEMSCAN BMA is done on two 90 cut polished sections, designed to limit bias related to the settling of heavy or large particles. The detection limit of BMA analysis can be as low as 0.01%, but care should be taken to
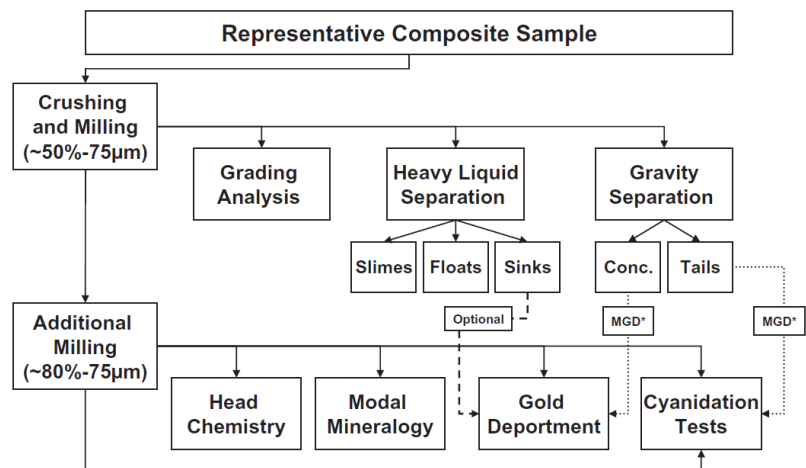

*Figure 1: Gold deportment testwork options. Cyanidation tests include direct cyanidation and diagnostic leaching. A full gold deportment study cannot always be done on the head material due to time and cost constraints, the gold deportment is then done on a gravity concentrate and diagnostic leach tests on the gravity tailings. *MGD = "Modified Gold Deportment Study".*

validate the BMA data against the XRD mineral identification and XRF chemical composition.

Optical microscopy is employed to identify carbonaceous components (e.g. kerogen) not easily identified by XRD or BMA.

For sulphide-rich ores, the sulphide characteristics may be investigated in detail since the sulphide characteristics may influence the processing route. An aliquot of 100 g is split from each composite sample (80% passing 75 μm) and screened into three size fractions (+75 μm, +38 μm/75 μm, and 38 μm). Polished sections are prepared from the different size fractions and analysed by QEMSCAN Specific Mineral Search (SMS) in order to determine the sulphide liberation, mineral association and size distribution.

2.7. GOLD DEPORTMENT (BY AUTOMATED MINERALOGICAL TECHNIQUE)

Depending on the gold grade of the sample, between 12 and 48 polished sections are prepared from the 80% passing 75 μm material. QEMSCAN Trace Mineral Search (TMS) analyses are conducted on these polished sections, in order to locate and describe the particulate gold occurrences. Furthermore, several polished sections prepared from the HLS sinks fraction and/or gravity concentrate may also be analysed by TMS. This is done in order to minimize the problems related

to representivity due to the "nugget effect", especially when the sample contains relatively coarse grained gold. Each gold-containing particle is mapped mineralogically and the particle maps are stored in a database. Certain characteristics are quantitatively extracted from this database, these include:

a. Gold mineral type and proportions (e.g. native gold vs. aurostibite or Au-tellurides).

b. Gold-containing particle characteristics (e.g. particle composition, particle size distribution and particle SG).

c. Gold exposure (% of gold grains exposed vs.% of gold grains locked in gangue particles).

d. Gold mineral associations (especially mineral associations of locked gold grains).

e. Gold grain size distribution.

f. An estimate of the amount of sub-microscopic gold (solid solution or "invisible" gold). The estimate is obtained by calculating the particulate gold grade and subtracting it from the measured head grade.

2.8. CYANIDATION TESTS

A direct cyanidation test (at excess conditions) indicates the amenability of the ore to gold extraction by cyanidation.

These results are compared to the gold grain exposure determined during QEMSCAN analysis. The results should be similar, unless the sample contains a significant amount of sub-microscopic or solid-solution gold or if the gold is hosted by phases which leach very slowly or not at all (like aurostibite and Au-tellurides). If gold deportment analysis is only done on a concentrate sample, then diagnostic leach tests are done on the gravity tailings (Modified Gold Deportment Study). Diagnostic leach tests may also be done on a head sample and the results must agree with the gold deportment results. The procedure involves the sequential solubilising of the least-stable minerals via various pre-treatments, and extraction of the associated gold by cyanidation/Carbon in Leach (CIL). The tests are performed on split aliquots milled to 80% passing 75 μm.

Cyanidation can be used to determine the following:

a. To quantify the gold that can be extracted via direct cyanidation (i.e. free and exposed gold), a sub-sample is cyanided.

b. To quantify the gold that is preg-robbed, but which should be recoverable via CIL processing, a second sub-sample is cyanided in the presence of activated carbon.

c. To quantify the gold liberated by mild oxidative pre-treatment (occluded in carbonates, pyrrhotite, magnetite, etc.), the CIL residue is subjected to hot HCl followed by CIL dissolution of the acid-treated residue.

d. To quantify the gold occluded within sulphide minerals, the residue from the previous step is subjected to a severe oxidative pre-treatment using hot HNO3 followed by CIL dissolution of the acid-treated residue.

e. To quantify the gold associated with carbonaceous material such as kerogen, the subsequent residue sample is subjected to complete oxidation via roasting, followed by CIL dissolution of the calcine product. The gold remaining in the final residue is assumed to be occluded within silicate gangue.

The interpretation of the diagnostic leach results is sometimes difficult, especially if mineralogical data is not taken into consideration. For example, diagnostic leach tests on a recently studied sample indicated low direct cyanidation recoveries (65%). An additional 25% gold became available to cyanidation after mild oxidative pre-treatment (hot HCl), and it was assumed that this gold was locked in pyrrhotite and carbonate. However, the gold deportment analysis indicated that <1% of the particulate gold was locked in pyrrhotite or carbonates. In fact the particulate gold was very well exposed (>90%). Further investigation showed that the sample contains significant amounts of aurostibite, arsenic- and antimony-sulphide minerals as well as oxygen consuming marcasite and pyrrhotite. These sulphides interfered with the cyanidation chemistry by consuming cyanide and oxygen and forming passivation rims around gold grains during cyanidation. Thus, the HCl pre-treatment really only acted as a washing step and some of the passivation rims may have been dissolved. As a consequence of all this, the cyanidation chemistry was subsequently changed by adding lead nitrate and kerosene and the direct cyanidation recoveries improved dramatically (90%). If the mineralogy was ignored, a considerable amount of money would have been wasted on a testwork program to recover the "locked" gold (flotation, ultra-fine grinding and even high pressure leaching).

3. REASONS FOR POOR GOLD EXTRACTION

Cyanidation is the most commonly used technique for extracting gold from ore by converting the gold to water soluble aurocyanide metallic complex ions (Marsden and House, 1992). The dissolved gold is usually recovered by the Carbon-in-Leach (CIL) or Carbon-in-Pulp (CIP) process (Marsden and House, 1992). Depending on the response to cyanide leaching, gold ores can be classified as "free milling" or "refractory" (Marsden and House, 1992). High gold recoveries (>90%) can readily be achieved from free milling ores, while refractory gold ores are characterized by low gold recoveries (<80%). There is no single cause for poor gold extraction, but rather a range of causes, which can be identified during the gold deportment study. For refractory gold ores and concentrates a suitable pre-treatment process is required to render the gold amenable to cyanidation.

Pre-treatment options include roasting, pressure oxidation, bio-oxidation, ultra-fine grinding and modified cyanidation, often preceded by a concentration step such as gravity separation or flotation (Marsden and House, 1992). The identification of different problems and possible solutions are discussed below.

3.1. POOR GOLD GRAIN EXPOSURE

The degree of gold grain exposure is measured using an automated electron microscopic technique (QEMSCAN). Very fine (normally <10 μm in size) particulate gold, locked in sulphide or other gangue, may not be exposed to cyanide solutions at "normal" grinds (e.g. 80% passing 75 μm). This may require finer to ultra-fine grinding (e.g. 80% passing 20 μm or 80% passing 10 μm) to expose the particulate gold. Ultra-fine grinding is a physical method for the liberation of locked gold, but due to high energy requirements it is an expensive option. If the ultra-fine particulate gold is restricted to sulphides, upgrading by flotation/gravity and oxidative destruction of the sulphides by roasting, pressure oxidation or bio-oxidation could be possible processing options. During cyanidation, gold grains may also be encapsulated by newly formed precipitates, limiting the exposure of the gold grains to the cyanide solution. The possibility of the formation of these so-called "passivation rims" is related to the presence of antimony/arsenic-sulphide and pyrrhotite in the ore (Venter et al., 2004).

3.2. SOLID-SOLUTION (INVISIBLE) GOLD

Gold occurring in "solid-solution" or as sub-microscopic particles within the crystal structure of sulphides, such as pyrite, arsenian-pyrite, stibnite and arsenopyrite (Reich et al., 2005), can result in significant proportions of the gold reacting refractory to direct cyanidation. The amount of solid-solution gold in a sample is estimated from the gold deportment (difference between the particulate gold grade and measured gold grade)

Gold mineral	Approximate formula	Specific gravity	Dissolution rate	Dissolution (excess conditions)
Native gold	Au ± Ag (<25% Ag)	16.0–19.3	Fast	Very high
Electrum	Au–Ag (25–55% Ag)	13.0–16.0	Fast	Very high
Aurocupride	AuCu	11.5	Fast	Very high
Sylvanite	$AuAgTe_4$	8.2	Slow	Variable, high
Petzite	Ag_3AuTe_2	9.1	Slow	Variable, high
Hessite	Ag_2Te	8.4	Slow	Variable, high
Calaverite	$AuTe_2$	9.2	Slow	Moderate to low
Maldonite	Au_2Bi	15.5	Slow	Low but variable
Aurostibite	$AuSb_2$	9.9	Zero to very slow	None to very low

Table 1: Cyanide dissolution of selected gold minerals (modified after Venter et al., 2004).

and from the diagnostic leach test (gold recovered after aggressive pre-oxidation by hot HNO3).

The gold-bearing sulphide minerals are often recovered into a sulphide concentrate by gravity or flotation concentration, depending on the liberation characteristics of the sulphides. Gold present in solid-solution can only be effectively recovered if the mineral matrix is decomposed by some chemical or biological pre-treatment method. Roasting is one of the most common methods for the treatment of gold-bearing pyrite/arsenopyrite and pyrrhotite concentrates to produce porous calcine with an increased amenability to cyanidation. Pressure oxidation and bio-oxidation methods are more environmentally friendly than roasting.

3.3. GOLD SPECIATION

Gold predominantly occurs as native metal, often alloyed with silver. Since native gold has such a high specific gravity (16.0–19.3) it can be recovered by gravity concentration, provided the gold grains are liberated and coarse enough (>10 µm).

Native gold and electrum (gold containing 25–55% silver) are readily dissolved in cyanide solution (Marsden and House, 1992). Other naturally occurring gold minerals include alloys with antimony, tellurium, selenium, bismuth, mercury, copper, iron, rhodium and platinum. Some of these gold minerals are insoluble or sparingly soluble in cyanide solution (Table 1). Furthermore, some of the gold minerals display very slow leach kinetics, and in some instances, longer retention times may lead to higher gold recoveries. There are no naturally occurring gold oxides, silicates, carbonates, sulphates or sulphides (Marsden and House, 1992).The gold minerals are identified by Scanning Electron Microscope – Energy Dispersive

Spectroscopic (SEM–EDS) analysis. The proportions of the different gold minerals are determined by QEMSCAN analysis.

3.4. GANGUE MINERALOGY

The mineralogical composition of each sample is determined by a combination of X-ray Diffraction (XRD), optical microscopy, major element chemistry and Bulk Modal Analysis (BMA) by QEMSCAN. Emphasis is placed on the identification and quantification of deleterious components such as cyanide and oxygen consumers, preg-robbers and also other minerals that would pose difficulties during processing (such as natural floaters and clay minerals).

3.4.1. CYANIDE AND OXYGEN CONSUMERS

The presence of significant (often as low as <100 ppm) cyanide consumers, such as secondary copper minerals (e.g. chalcocite, covellite, malachite, azurite, etc.), could result in very high cyanide consumption. High cyanide consumption often results in low or inhibited gold recoveries, as the cyanide is preferably consumed by the more abundant copper phases before it can dissolve the gold. Copper forms stronger complexes with cyanide than gold and as a rule a five-to-one molar ratio of cyanide to soluble copper is required to leach gold (Venter et al., 2004). Precipitation of the Cu and Au as insoluble cyanide salts may also be the cause of lower gold recoveries. Higher levels of cyanide consumption may sway the economic viability of a project.

Oxygen is one of the reagents consumed during cyanidation, and a deficiency of dissolved oxygen in the leach solution will slow down the cyanidation reaction. Oxygen consumers, such as pyrrhotite and marcasite, can have a detrimental effect on cyanidation. The oxidation state of the leach, and a need for oxygen addition, should then be

closely monitored to optimize the leach performance. Pre-oxidation is a common step, where oxygen consumers are abundant. Air or pure oxygen gas can be bubbled through the pulp to increase the dissolved oxygen concentration.

3.4.3. OTHER DELETERIOUS MINERALS

If gold concentration by flotation is considered, the presence of natural floating minerals like pyrophyllite and talc becomes important (Chryssoulis, 2001). These minerals, if present in significantquantities, will report to the flotation concentrate, increase the mass pull and dilute the gold grade.

If clay minerals, like montmorillonite, are present in significant amounts, then problems related to solid–liquid separation will be encountered. Lower sold-liquid ratios may be required, which lowers the throughput of a processing plant. Clay minerals also reduce permeability in heap-leach operations.

Sulphide minerals further interfere by providing sulphide, arsenite/arsenate and antimonite/antimonate ions that form insoluble species on gold grain surfaces (Venter et al., 2004; Deschenes, 2005; Deschenes et al., 2009; Karimi et al., in press).

3.5. COARSE GOLD

The presence of coarse gold is indicated by the following results, obtained during the testwork program:

a. High assay variability (triplicate gold assay).

b. Gold upgrades into the coarser fractions during the grading analysis

a. High gold recovery by HLS and gravity (>40%).

b. Large portion of the gold grains >25 µm Equivalent Circular Diameter (ECD).

Coarse gold results in large assay uncertainties due to the "nugget effect", which influences the mine call and plant call factors. Furthermore, coarse gold requires longer retention times during cyanidation in order to achieve full dissolution. Incomplete dissolution of coarse gold leads to gold losses to the tailings. Investigation of various tailings samples from South African Witwatersrand ores indicated that tailings from certain reefs may contain relatively large liberated gold grains. These grains are rare and sporadic and normally unaccounted for when small tailings samples are assayed, resulting in an underestimation of the tailings grade.

When coarse gold is present, it is highly recommended that gravity concentration be part of the processing circuit. Furthermore, blasting should be done in such a way as to minimize the production of fines, since coarse gold is easily liberated and lost on the mine floor and during transportation of the ore. Theft of coarse gold is also a problem since the coarse gold is easily concentrated in suitable traps.

4. CASE STUDY: GOLD DEPORTMENT OF AN EAST AFRICAN GOLD ORE

Six composite samples from an east African gold ore deposit were submitted to SGS South Africa for gold deportment analysis. The samples were composed of reverse circulation drill chips (drill core is preferable, but was not available). Very little historical data was available and the mineralogy and gold deportment completely unknown. The composites were created by the exploration geologist, based on geology and spatial distribution. The objective

Sample	Head assays (Au g/t)							Avg. deviation
	A	B	C	D	E	F	Avg.	
Sample A	5.28	5.17	5.22	5.40	5.28	5.14	5.25	0.07
Sample B	7.71	7.89	8.12	8.02	8.26	–	8.00	0.16
Sample C	1.76	1.78	1.58	2.41	2.14	2.34	2.00	0.29
Sample D	4.00	4.20	4.01	4.50	–	–	4.18	0.17
Sample E	3.33	4.03	3.22	3.26	–	–	3.46	0.29
Sample F	6.01	7.26	7.64	6.94	6.87	6.78	6.92	0.36

Sample	Head assays (Ag g/t)					Avg. deviation
	A	B	C	Avg.	Ag:Au ratio	
Sample A	11	12	13	12	2.3	0.67
Sample B	15	15	14	15	1.8	0.44
Sample C	3	3	3	3	1.5	0.00
Sample D	9	10	9	9	2.3	0.44
Sample E	8	9	8	8	2.4	0.44
Sample F	3	3	3	3	0.4	0.00

Table 2: Head grades of the six composite samples from an East African gold deposit.

of the study was to understand the mode of occurrence of gold, in order to ascertain a possible cost effective and practical process route. The project was in the pre-feasibility stage and the client required a fast and inexpensive testwork program. Therefore the "Modified Gold Deportment" approach was followed.

4.1. CHEMICAL AND MINERALOGICAL COMPOSITION

The head gold and silver assays are given in Table 2. The average gold grade varied between 2.00 g/t and 6.92 g/t. The average silver grade varied between 3 g/t and 15 g/t.

Generally, the silver to gold ratio was between 1.5:1 and 2.4:1, except for sample F, where the ratio of silver to gold was 0.4:1. The average silver to gold ratio for all the samples (equal weights) was 1.8:1, thus the silver content was on average almost double the gold content.

The chemical compositions as determined by AAS, XRF, and Leco (Table 3) revealed that the samples contained high amounts of SiO2, Al2O3, CaO, Fe2O3, and Na2O. This indicated a possible high quartz and feldspar composition. The total sulphur content of the samples varied between 0.33% and 1.41%, indicating variability and low sulphide content. The arsenic content of the samples was relatively low (20–66 ppm), therefore arsenopyrite was not expected to be present in major amounts.

XRD analysis revealed that the samples were mineralogically fairly similar. All six samples were primarily composed of quartz, muscovite, albite and calcite with minor pyrite. In addition some samples contained chlorite and minor amounts of ankerite. The QEMSCAN modal analyses agreed with the XRD results. Data validation was done by comparing the calculated chemical composition to the measured chemical composition

Table 3: Chemical compositions of the East African gold ore samples as determined by XRF, AAS, and Leco. LOI = Loss on ignition.

Element	Sample A	Sample B	Sample C	Sample D	Sample E	Sample F
SiO_2	79.7	64.8	81.1	79.5	76.6	66.2
Al_2O_3	8.62	12.5	4.31	10.00	7.47	10.4
CaO	1.48	4.05	2.24	0.61	3.29	5.16
MgO	0.47	1.84	0.54	0.25	1.32	1.12
Fe_2O_3	1.73	5.16	3.72	1.54	3.54	4.24
K_2O	0.70	1.70	1.23	0.75	0.94	2.48
MnO	0.03	0.06	0.04	0.01	0.05	0.05
Na_2O	3.34	3.47	0.36	3.97	1.97	1.53
P_2O_5	0.02	0.18	0.06	0.04	0.12	0.11
TiO_2	0.11	0.65	0.2	0.14	0.42	0.39
Cr_2O_3	<0.01	<0.01	<0.01	<0.01	0.04	<0.01
V_2O_5	<0.01	0.01	<0.01	<0.01	<0.01	<0.01
LOI	2.36	5.33	3.7	1.4	3.04	6.34
Total	98.6	99.8	99.7	98.2	98.8	99.7
Total S	0.33	1.12	1.41	0.62	0.80	0.94
As (ppm)	50	66	38	20	42	38

Mineral	Approx. formula	A	B	C	D	E	F
Quartz	SiO_2	56.66	32.80	73.75	51.98	57.96	45.01
K-Feldspar	$KAlSi_3O_8$	0.37	0.90	1.09	0.52	0.48	1.30
Plagioclase	$NaAlSi_3O_8$	32.23	32.75	5.88	37.67	19.22	16.51
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$	6.08	16.44	10.53	6.62	8.84	23.15
Chlorite	$(Mg, Fe)_3(Si, Al)_4O_{10}(OH)_2 \cdot (Mg, Fe)_3(OH)_6$	0.22	7.08	0.43	0.43	4.97	1.84
Zircon	$ZrSiO_4$	0.01	0.06	0.02	0.01	0.03	0.03
Sphene	$CaTiO(SiO_4)$	0.00	0.05	0.00	0.00	0.04	0.02
Silicates		*95.58*	*90.08*	*91.69*	*97.23*	*91.53*	*87.87*
Pyrite	FeS_2	0.62	2.16	2.64	1.23	1.27	1.70
Chalcopyrite	$CuFeS_2$	0.00	0.01	0.04	0.00	0.02	0.01
Galena	PbS	0.01	0.00	0.01	0.00	0.01	0.00
Sulphides		*0.63*	*2.18*	*2.69*	*1.23*	*1.30*	*1.71*
Fe-oxide/hydroxide	$FeO-Fe_2O_3-FeOOH$	0.56	1.22	1.01	0.56	1.20	0.78
Chromite	$FeCr_2O_4$	0.02	0.03	0.02	0.01	0.02	0.03
Ilmenite	$FeTiO_3$	0.00	0.04	0.00	0.00	0.02	0.00
Rutile	TiO_2	0.05	0.35	0.11	0.07	0.28	0.20
Oxides		*0.62*	*1.64*	*1.14*	*0.64*	*1.51*	*1.01*
Apatite	$Ca_5(PO4)_3(OH)$	0.03	0.32	0.14	0.06	0.26	0.21
Carbonates	$Ca,Mg(CO_3)_2$	2.91	5.40	4.04	0.68	5.17	8.97
Carbonates, phosphates and sulphates		*2.95*	*5.72*	*4.19*	*0.74*	*5.43*	*9.19*
Other		0.22	0.39	0.29	0.18	0.22	0.22
Total		100.00	100.00	100.00	100.00	100.00	100.00

Table 4: Mineralogical compositions of the East African gold ore samples.
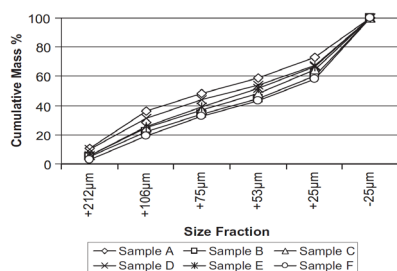

Figure 2: Cumulative grain size distribution after crushing and milling (50% passing 75 µm).
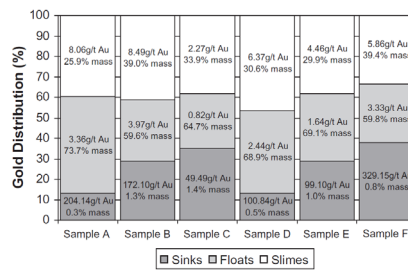

Figure 4: Results of the heavy liquid separation analyses.

Figure 3: Gold and silver upgrade or downgrade per size fraction. Note the strong upgrade of both gold and silver into the 25 µm fraction.

of the head samples and indicated good agreement. The mineralogical compositions of the samples are given in Table 4. The samples contained between 0.63% and 2.69% sulphides. The main sulphide mineral was pyrite, but trace amounts of chalcopyrite, galena and arsenopyrite were also observed.

4.2. DIRECT CYANIDATION

In order to determine the amenability of the ore to direct cyanidation, a split aliquot of each sample was milled to 80%–75 µm and cyanided. The leach parameters were: 1:1 liquid to solid ratio; 1 h pre-conditioning; 48 h dissolution period; 20 g/l carbon addition; 5 kg/t cyanide addition; CaO addition varied to keep pH at 11. The leach tests indicated that between 81% (Sample A) and 88% (Sample F) of the gold was recoverable by direct cyanidation. The samples were therefore classified as partly refractory.

4.3. GRADING ANALYSIS

Grading analysis indicated that most of the samples were finer than the target grind of 50% passing 75 µm (Fig. 2), with a relatively large proportion of the material in the 25 µm size range. The skew particle size distribution is probably a function of the preparation of the composite samples from air percussion drill chips, which contained a large proportion of fine-grained material. In order to display the relative upgrading or downgrading of gold and silver into the different size fractions, the elemental
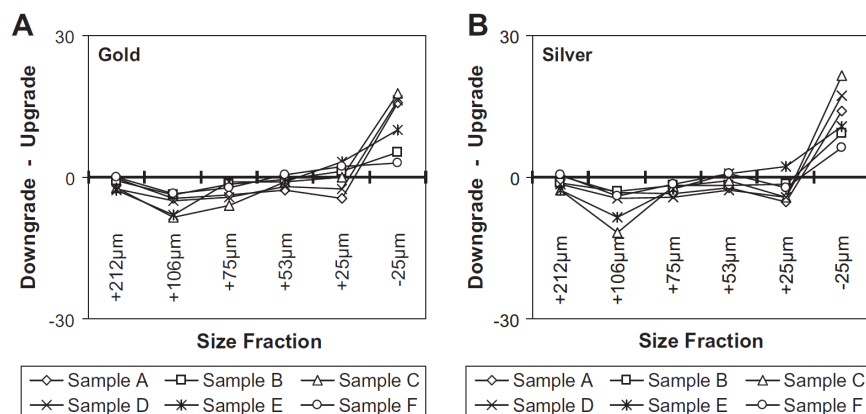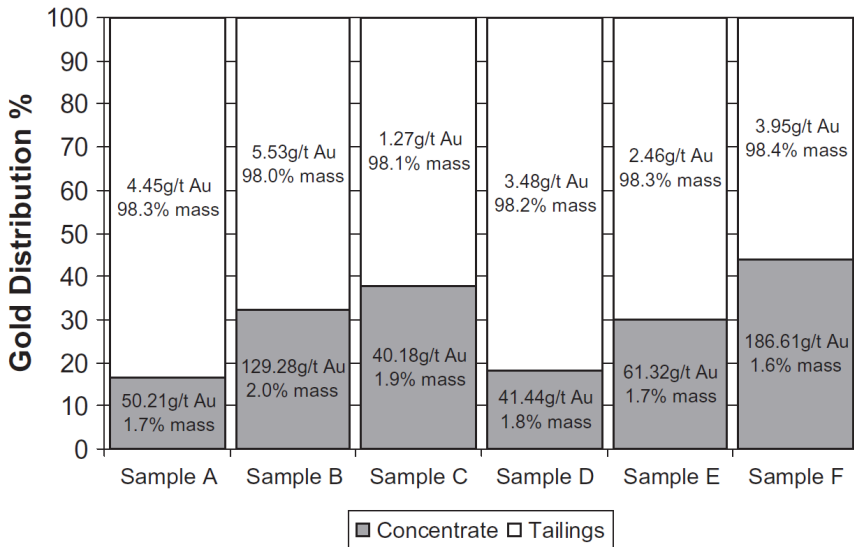
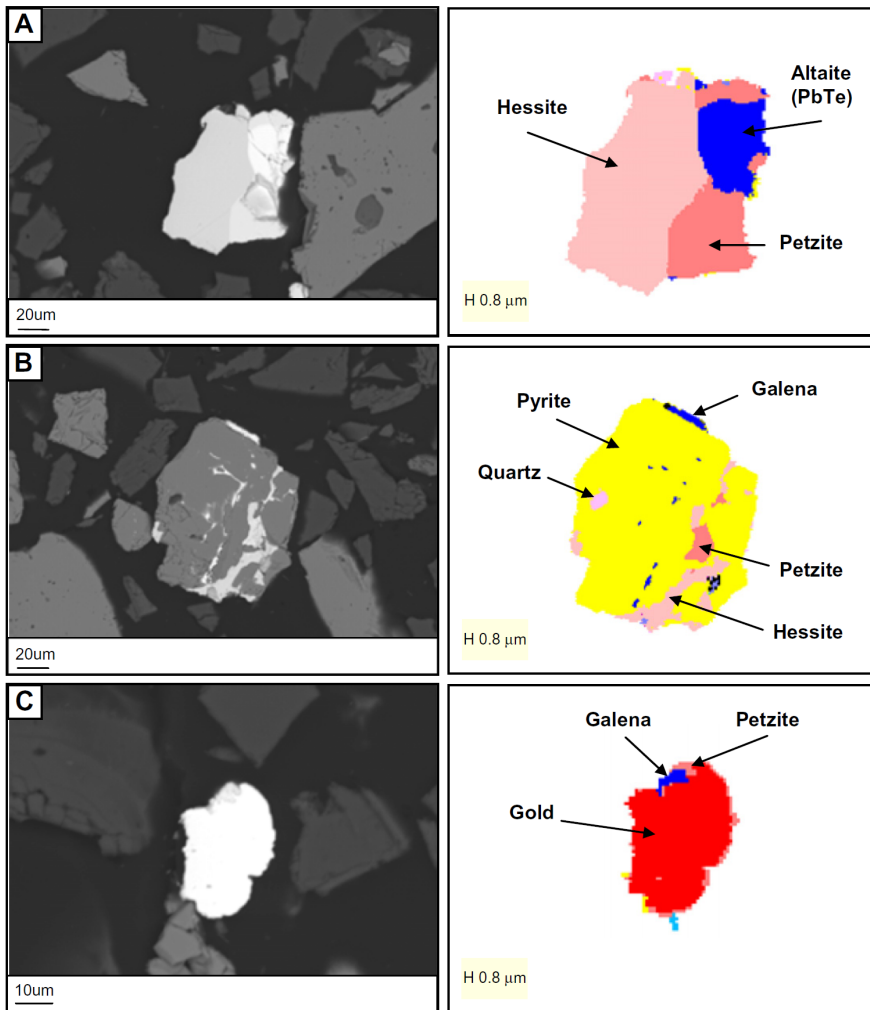Figure 5: Results of the gravity separation analyses.

Figure 6: SEM Backscattered electron images and accompanying QEMSCAN particle maps of a few gold mineral containing particles. (A) Association of hessite and petzite (>90% grain exposure). (B) Association of hessite, petzite and pyrite. (C) Liberated native gold grain.

distribution (in percent) is subtracted from the mass distribution (in percent).

The resulting graphs are presented in Figs. 3. From the graphs it is clear that gold and silver preferentially reports to the 25 µm fraction, indicating that the gold/silver grains are predominantly fine-grained. As a quality control measure, the calculated head grades were compared to the average head grades. The calculated and measured grades were very similar, which indicated good assay quality.

4.4. HEAVY LIQUID SEPARATIONS (HLS) AND GRAVITY SEPARATION

The results of HLS analyses are given in Fig. 4. There is an upgrade of gold into the slimes fraction (25 µm) for all the samples except Sample F. The gold recoveries into the sinks varied between 13% and 38%, indicating that gravity upgrading might not be a viable processing option.

Due to the time and cost constraints of the project, it was decided to pre-concentrate the gold grains by gravity separation and to only analyse polished sections prepared from the gravity concentrates for their particulate gold deportment. Since a large proportion of the gold reported to the gravity tailings (Fig. 5), diagnostic leach tests were performed on the gravity tailings, thereby obtaining a full picture of the gold deportment of each sample.

The gravity testwork results compared well with the HLS results. Gold recoveries by gravity are slightly better than HLS, at slightly higher mass pulls. The total gold recovery by gravity concentration varies between 17% and 44%. Gold in the gravity tails could possibly be attributed to several factors, namely:

a. Very fine-grained liberated gold not amenable to gravity concentration, due to entrainment by the silicate/carbonate gangue.

b. Very fine-grained, locked/attached gold associated with light gangue (silicates/carbonates).

c. Sub-microscopic or 'invisible gold' associated with relatively fine-grained sulphides which were not recovered by gravity concentration (low middling or locked sulphides).

Three polished sections were prepared from each gravity concentrate for QEMSCAN Trace Mineral Search (TMS) analyses.

4.5. GOLD DEPORTMENT OF PARTICULATE GOLD IN THE GRAVITY CONCENTRATES

The QEMSCAN was set up to find and map particles containing areas of high backscattered electron (BSE) intensity (including gold grains). Three polished sections of the gravity concentrate of each sample were scanned. The gold grains observed in the concentrates only represent 17–44% of the total gold. The gold that reported to the gravity tails was characterized by diagnostic leach tests. A total of 4226 gold-containing particles were mapped and these particles contained 12,986 gold/silver grains. A selection of backscattered electron images of gold bearing grains and their corresponding QEMSCAN particle maps are presented in Fig. 6.

SEM-EDS analyses revealed that gold is present as native gold (AuAg, with low, but variable amounts of silver), as petzite (Ag3AuTe2) and in hessite (Ag2Te, with 1.4–4.7% gold). The gold elemental deportment in these minerals is given in Fig. 7. The large variability in the gold speciation will cause inconsistent cyanidation leach recoveries.

4.6. GOLD GRAIN EXPOSURE AND MINERAL ASSOCIATION

The grain exposure gives an indication of the leachability of an ore at a specific grind. The exposure of the gold grains in the gravity concentrates (milled to 50%–75 μm) varied between 65% and 85% (Table 5 and Fig. 8), except for Sample D, where the exposure was only 40%. Most of the locked gold was locked in pyrite and very little locked in silicates. The exposure analysis is only valid for the gold grains in the gravity concentrates, the exposure of the gold grains in the gravity tails was inferred from diagnostic leaching to be between 79% and 87%.

All the gold minerals were combined for the grain size distribution analysis. Generally the grains are very fine, mostly <25 μm (between 57% and 100%), with a significant amount smaller than 5 μm (between 17% and 46%). The cumulative grain size distribution of the locked gold/
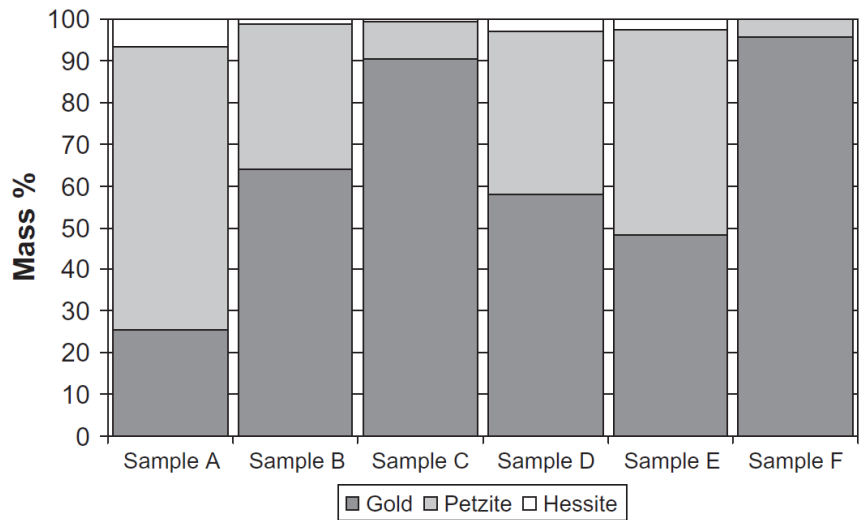

Figure 7: Gold elemental deportment by gold mineral. Note the high petzite content of sample A relative to sample F; this large variability will cause inconsistency in the cyanide leach recoveries.
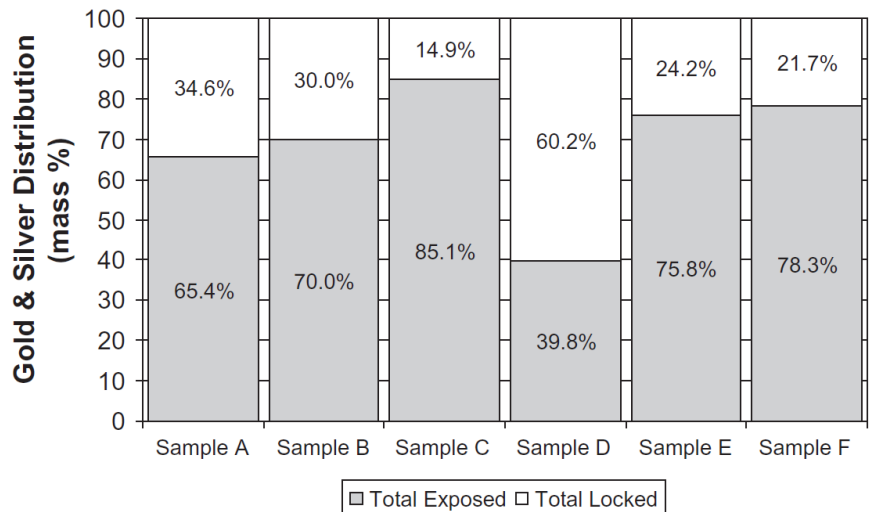

Figure 8: Gold/silver grain exposure of the particulate gold observed in the gravity concentrate samples.

silver grains (Fig. 9) indicates that an additional amount of 35% to 47% of the locked gold could be exposed by ultra-fine milling of the gravity concentrate to 100%–10 μm.

4.7. DIAGNOSTIC LEACH RESULTS OF THE GRAVITY TAILINGS

Since the gold lost to the gravity tails was not characterized, diagnostic leach tests were conducted on the gravity tailings. A split aliquot of the gravity tails of each sample was milled to 80%–75 μm for the testwork.

Between 79% and 87% of the gold in the gravity tailings was recoverable by direct cyanidation (Table 6). This compared well to the results of the

direct cyanidation of the head samples (81–88%). HCl digestible minerals include the carbonates, some chlorite and some of the oxides, like magnetite. Between 1.4% and 6.6% of the gold was locked in these minerals. However, the largest fraction of locked gold was exposed by strong acid (HNO3) leach (up to 14%) suggesting that this fraction of the gold was locked in pyrite. Between 2% and 12% of the gold was locked in the final residue, suggesting that these are very fine gold grains locked in remnant silicates such as quartz and feldspar. Only ultra-fine grinding would liberate some of these fine gold grains.

Exposure and association categories	A	B	C	D	E	F
Exposed (≥80%)	39.05	24.12	69.21	15.14	31.17	46.38
Exposed (≥10% <80%)	23.64	38.48	9.72	18.28	40.08	29.94
Exposed (<10%)	2.73	7.38	6.13	6.38	4.55	1.94
Total exposed	65.41	69.98	85.07	39.80	75.80	78.26
Locked in sulphide (100%)	29.08	28.38	13.22	53.44	19.88	15.69
Locked in silicate (100%)	2.10	0.31	0.14	1.13	0.04	0.31
Locked in oxide (100%)	0.01	0.02	0.00	0.04	0.19	0.03
Locked in carb/phos/sulphates (100%)	0.08	0.03	0.06	0.44	0.01	0.01
Locked on sulphide-silicate boundary	1.13	0.15	0.27	2.91	0.50	2.37
Locked on sulphide-oxide boundary	0.01	0.43	0.08	0.00	0.13	0.03
Locked on sulphide-carb/phos/sulphate boundary	0.09	0.18	0.11	0.46	0.45	1.64
Locked on silicate-oxide boundary	0.00	0.00	0.00	0.07	0.49	0.07
Locked on silicate-carb/phos/sulphate boundary	1.18	0.06	0.07	0.03	0.01	0.02
Locked on poly-mineral boundary	0.90	0.47	0.98	1.67	2.50	1.58
Total locked	34.59	30.02	14.93	60.20	24.20	21.74
Total	100.00	100.00	100.00	100.00	100.00	100.00

Table 5: Exposure and association characteristics of the gold/silver grains.

Gold association	Sample A		Sample B		Sample C		Sample D		Sample E		Sample F	
	g/t	%	g/t	%	g/t	%	g/t	%	g/t	%	g/t	%
Directly cyanidable	3.24	79.21	4.25	80.51	0.99	80.10	2.87	86.24	2.11	87.13	3.07	84.97
Preg-robbed – CIL	0.07	1.81	0.07	1.30	0.00	0.29	0.01	0.27	0.00	0.17	0.03	0.94
HCl digestible minerals	0.27	6.60	0.23	4.26	0.03	2.52	0.05	1.37	0.04	1.82	0.09	2.39
HNO$_3$ digestible minerals	0.02	0.56	0.01	0.18	0.17	14.17	0.28	8.48	0.18	7.31	0.32	8.78
Carbonaceous matter	0.01	0.20	0.50	9.40	0.01	0.62	0.02	0.56	0.01	0.54	0.01	0.33
Quartz (balance)	0.47	11.62	0.23	4.35	0.03	2.30	0.10	3.08	0.07	3.03	0.09	2.59
Total	4.09	100.00	5.27	100.00	1.23	100.00	3.33	100.00	2.42	100.00	3.62	100.00

Table 6: Results of the diagnostic leach tests.

4.8. CASE STUDY OUTCOMES

The key case study outcomes are summarized below:

- Gold recovery by gravity concentration would not be a viable processing option, since most of the gold (56–83%) was not recoverable at a decent mass pull.

- The exposure of the gold grains in the gravity concentrates (milled to 50%–75 µm) varied between 65% and 85% except for Sample D, where the exposure was only 40%. Finer milling might therefore be required to expose the locked gold grains.

- Most of the locked gold was locked in pyrite (13–53%) and very little of the gold was locked in silicates (up to 11.6%, generally <5%). A large proportion of the gold may be recoverable by sulphide flotation.

- The exposure analysis is only valid for the gold grains in the gravity concentrates. The exposure of the gold/silver grains in the gravity tails was inferred from diagnostic leaching to be between 79% and 87%.

- Gold recoveries of between 81% and 88% by direct cyanidation at a grind of 80%–75 µm were achieved.
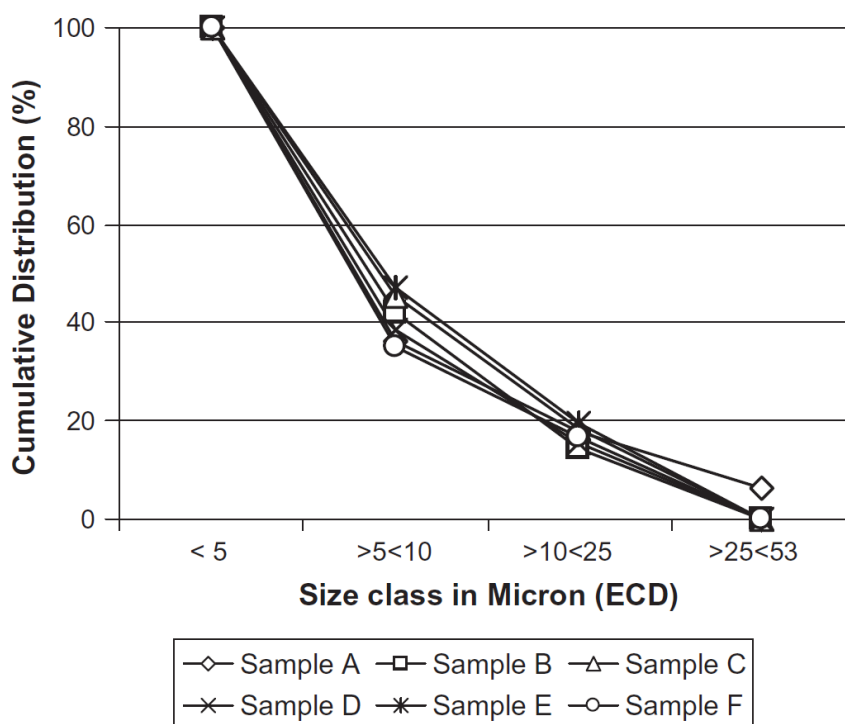

Figure 9: Cumulative grain size distribution of the locked gold/silver grains (gravity concentrate).

- The locked gold grains were very fine-grained. Further grinding, perhaps to 80%–53 µm, might increase the recoveries above 90%.

- The fact that gold occurs as both native gold and gold-tellurides (hessite and petzite) flag the possibility of low and variable leach kinetics. More intensive leach conditions (longer retention times, more cyanide and higher dissolved oxygen) may be required to improve gold recovery.

- A possible process route to recover the bulk of the gold and silver would be to mill the ore to 80%–53 µm followed by cyanidation (CIL).

- A second possible processing route would be to upgrade the gold and sulphides into a sulphide concentrate followed by oxidative destruction of the sulphides by roasting or bio-oxidation followed by cyanidation.

Additional metallurgical testwork was done on a bulk sample (simulated run-of-mine) and the following results were obtained, which confirm the gold deportment predictions:

- Gravity concentration yielded a concentrate containing 34.94% of the gold, assaying 67.73 g/t, collected in 2.57% of the feed mass (head gold grade 5.13 g/t). Intensive cyanidation of the gravity concentrate sample resulted in 94.2% gold dissolution (24 h, 3.68 g/t Au residue).

- Dissolution tests showed that finer grinding (from 80% passing 75 μm to 80% passing 53 μm) resulted in an increase in gold dissolution from 85.93% to 89.90% (48 h).

- Gold dissolution increased from 87.5% to 89.49% with an increase in cyanide addition from 1 kg/t to 2 kg/t (48 h, 80% passing 53 μm).

- Gold dissolution increased from 88.42% to 88.96% by increasing the retention time from 24 to 48 h (80% passing 53 μm).

- Gold dissolution increased from 88.96% to 89.93% by increasing the dissolved oxygen (DO) content from natural DO to elevated levels of 15 ppm DO (80% passing 53 μm and 2 kg/t NaCN).

5. CONCLUSIONS

Modern gold deportment studies aim to fully and quantitatively characterize representative gold ore samples using a combination of mineralogical and metallurgical techniques, in a time- and cost-effective manner. Potential metallurgical problems and ore variability are identified early on in the testwork phase so that subsequent metallurgical testwork can focus on optimising gold recovery through the most effective processing route. Application of the gold deportment methodology to a wide variety of samples demonstrates the value of modern gold deportment studies.

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