

Western Australian School of Mines

Department of Metallurgical and Minerals Engineering

**A Study of the Behaviour of Free Gold in
Flash Flotation and Gravity Recovery**

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

A handwritten signature in black ink, reading "Teresa Diane Hayward McGrath". The signature is written in a cursive style with a large initial 'T' and 'M'.

Teresa Diane Hayward McGrath

25 November 2014

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Abstract

As free-milling gold ore bodies are inevitably becoming depleted, the gold industry is instead being forced to process deposits with complex mineralogy. Some complex ores, for example ores containing sulfides, high copper and poly-metallic ores, and preg-robbing ores, which are not be readily amenable to cyanidation either for economic or technical reasons, may contain enough free (liberated) gold to be targeted for the recovery within the circulating load of the milling circuit. Due to its malleability, gold does not comminute well, and the dense metal will build up in the circulating load of the milling circuit until either it is fine enough to report to the cyclone overflow or it reports to the concentrate of a gravity or flash flotation unit. Removal of free gold in the milling circuit prevents large recirculating loads of free gold or incomplete leaching of coarse particles downstream and thus has potential economic advantages for the site.

Although gravity recovery and flash flotation in a closed loop milling circuit are employed worldwide to reduce the build-up of free gold within the mill, this arrangement is poorly understood and consequently, it is difficult to predict circuit performance. Views about the behaviour of gold in the milling circuit vary, with some based on scientific principles and others based on anecdotal evidence. Identifying the impact that changes in mineralogy, reagent use, operational factors, and physical variables (such as size, shape, surface area and elemental composition) will have upon the behaviour of free gold particles will lead to an improved understanding of the behaviour of free gold being recovered within the milling circuit. This knowledge can then be used to make predictions about free gold recovery, helping to model and improve performance of gravity and flash flotation circuits, and overall circuit optimisation.

As part of this research, a reproducible flash flotation method was developed to characterise the ultimate Flash Recoverable Free Gold (FRFG) content of an ore and, for the first time, batch flash flotation tests were conducted on a gravity concentrate to determine the effect of operational conditions and reagent additions on the recovery of free gold. The effects of airflow and frother, at the tested levels,

appeared to have no significant impact upon free gold recovery whether evaluated independently or in conjunction with the other four factors which were evaluated. Of the remaining factors, agitation, collector and sulfide addition exhibited variable responses when evaluated independently or in combinations. Surprisingly, the use of copper sulfate as an activator appeared deleterious for the recovery of free gold in testwork of this research.

The development of the flash flotation for free gold test standard operating procedure (SOP) allowed for kinetic studies of size by size flotation recoveries for gold particles of varying genesis (gold powder particles and gravity concentrates) as a function of collector addition. Previously, no published studies existed to demonstrate the size by size kinetic flotation recoveries of free gold and pure gold in laboratory flash flotation testwork. The results prove that larger particles of gold required more collector and residence time than smaller particles of similar composition, as would be expected in the FRFG system. The pure gold particles were better recovered by collectorless flotation although highest ultimate recoveries were achieved with gravity concentrates at the highest level of the collector potassium amyl xanthate (PAX) tested. Kinetic evaluations and recovery data indicate both the intermediate and some of the fine gold particles were satisfactory candidates for flash flotation as suitable portions could be recovered in the first 30 seconds of laboratory testing.

Finally, testwork was conducted on mill samples of gravity and flash flotation concentrates to identify variations in physical parameters (size, shape, composition, surface area and roughness) of gold particles found in concentrate samples as determined from two dimensional (2D) Quantitative Evaluation of Minerals by Scanning electron microscopy (QEMSCAN) and three dimensional (3D) Micro Computed Tomography (Micro CT). No other published studies exist in which the types of gold particles recovered in the concentrates of the flash flotation and gravity circuits operating in parallel within the milling circuit units are compared. This research is also the first attempt at comparisons of the 2D and 3D shape analysis for free gold particle characterisations. It was determined that appropriate techniques are

not in common practice to adequately describe gold particle shape and sufficiently resolve differences between particles in the concentrates. Despite the lack of quantitative shape and size analysis, qualitative results suggest the gravity units are superior at recovery of free gold in all size fractions. Additionally, the 2D and 3D shape determinations are contradictory. While 2D data support the common belief that is generalised as gravity concentrates would contain a higher proportion of spherical particles while flash flotation would be favoured for flat or flaky particles, the 3D data suggest the opposite is the case.

It is important to note that other publications on flash flotation have always focused on, and sometimes confused the behaviour of gold with the behaviour of pyrite, as gold is often associated with sulfides. This thesis focuses on and reports for the first time, the behaviour and characterisation of free gold in the milling circuit, with specific interest in the flash flotation recoverable component of the free gold contained in the recirculating load of the milling circuit.

List of Abbreviations and Acronyms

2D	(two dimensional)
3D	(three dimensional)
AAS	(atomic absorption spectroscopy)
Ag	(silver)
AIC	(Akaike information criterion)
ANOVA	(analysis of variance)
AR	(analytical reagent)
Au	(gold)
BCC	(batch centrifugal concentrator)
CaCO ₃	(calcium carbonate)
CaO	(calcium oxide)
CFS	(Corey shape factor)
CIL	(carbon in leach)
CIP	(carbon in pulp)
CMC	(carboxymethyl cellulose)
CSIRO	(Commonwealth Scientific and Industrial Research Organisation)
CuSO ₄	(copper sulfate)
DOE	(design of experiments)
FRFG	(Flash Recoverable Free Gold)
GRG	(gravity recoverable gold)
HDPE	(high density polyethylene)
ICP-MS	(Inductively coupled plasma mass spectrometry)

IOCG	(Iron oxide copper-gold)
JKMRC	(Julius Kruttschnitt Mineral Research Centre)
LPM	(litres per minute)
MAPE	(mean absolute percentage error)
MIBC	(methyl isobutyl carbinol)
Micro CT	(Micro Computed Tomography)
Na ₂ S	(sodium sulfide)
NaCN	(sodium cyanide)
OFAT	(one factor at a time)
PAX	(potassium amyl xanthate)
p-value	(calculated probability, used for significance testing in statistics)
QEMSCAN	(quantitative evaluation of minerals by SEM)
RIP	(resin in pulp)
RPM	(rotations per minute)
RSM	(response surface methodology)
SCE	(saturated calomel electrode)
SEM	(standard hydrogen electrode)
SHE	(scanning electron microscopy)
SOP	(standard operating procedure)
TKE	(turbulent kinetic energy)
UFG	(ultrafine grinding)
VMS	(Volcanogenic massive sulfide)
WAD	(weak acid dissociable)

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I dedicate this thesis to my husband, Jeff, and children, Lucas and Olivia. There is no better measure of commitment than setting aside your own aspirations to relocate to a different continent in support my ambitions. Without your daily reassurance, I would never have had the confidence and endurance to finish this project. I love and appreciate you all so very much.

Publications

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CHAPTER 1. INTRODUCTION

Throughout history, the occurrence of native or “free” gold was common enough to warrant simple forms of gravity recovery based on density. This was possible because of pure gold’s high density (19.3 g/cm^3) in relation to common gangue material, such as silicates ($\sim 2.7 \text{ g/cm}^3$). There was little need for chemical or metallurgical processing when there was an abundance of ore bodies containing such sources of dense free gold. Free-milling, or cyanidable, sources of gold are becoming infrequent and the gold industry is now turning to deposits with more complex mineralogy (such as ores containing sulfides, high copper and poly-metallic ores, and preg-robbing ores) to meet market demands.

While the gold industry currently processes most ores via cyanide leaching and carbon adsorption (Laplante and Gray, 2005), the complex ores more recently targeted are not easily amenable to cyanidation either for economic, environmental or technical reasons. Recovery of gold from ores with complex mineralogy requires elaborate circuits incorporating innovative unit operations and sometimes novel circuit configurations.

Some of these complex ores which are not readily amenable to cyanidation may contain enough elemental gold to be targeted for recovery within the circulating load of the milling circuit. Free gold is malleable and does not comminute well, therefore, it may require 50-100 passes through the milling circuit until it is sufficiently fine enough to report to the downstream process (Laplante, 2000). This means that free gold much smaller than the intended cut size of the bulk material (for example $20 \mu\text{m}$ vs. $57 \mu\text{m}$) will report to the cyclone underflow and be retained in the milling circuit until sufficient size reduction has occurred for the material to report to cyclone underflow (Banisi et al., 1991). Build-up of free gold in the milling circuit also occurs due to the element’s high density, compared to gangue material. Free gold content in the recirculating load can often be over 1000% (compared to sulfide minerals around 200%) and thus it is sensible to target recovery of gold from within the milling circuit as it provides a high grade feed source. Removal of free

gold in the milling circuit, achieved via either gravity recovery and/or flash flotation, reduces large recirculating loads of free gold and can lessen the impact of incomplete leaching of coarse particles downstream.

In principle, gravity concentration methods separate dense particles (such as gold) from lighter gangue materials based on their response to gravity and the movement of a viscous fluid, usually, water (Koppalkar, 2009; Wills, 2006) while flash flotation was originally designed to be used ahead of conventional flotation in grinding mill circulating loads in order to reduce the over-grinding of sulfides (Bourke, 2002). The strategy of gravity and flash flotation operating within a closed loop milling circuit has been employed by many mills worldwide over the last couple of decades to reduce the circulating load and process complex ores containing liberated “free” gold as well as gold in a sulfide matrix, unliberated or refractory gold. When the two types of concentrators are acting upon the same feed stream the literature suggests that gravity recovery of coarse free gold will be preferred because free gold greater than 200 μm cannot be floated effectively (Malhotra and Harris, 1999). Gravity recovery units target large, dense particles and will have diminished efficiency with reduction in particle size. For example, on average, the most popular type of gravity recovery units, batch centrifugal concentrators (BCCs), will recover 40 % of +38 μm gold particles and only 10 % of -38 μm gold particles (Chryssoulis and Dimov, 2004). Laplante and Dunne (2002a) found that those -38 μm free gold particles unlikely to be recovered in the gravity circuit can be captured in the flash flotation circuit. They also suggest that free gold particles larger than 212 μm will preferentially report to a gravity concentrator when gravity and flash flotation are operated in a closed loop milling circuit, leaving an intermediate -212/+38 μm fraction with an unquantified propensity for either recovery mechanism.

In investigating the relationship of gravity and flash flotation for recovery of free gold particles, the following ranges have been identified as sizes of interest in this project: +212, -212/+38 (or just +38) and -38 μm . For ease of discussion, these size classes are also referred to as coarse, intermediate, and fine, respectively throughout the remainder of this dissertation. Particles in the intermediate size

fraction or -212/+38 μm are of particular interest, as this has been identified as the zone of competition between the gravity and flash flotation units. In ideal cases, such as the relationship demonstrated in Figure 1-1, large particles of gold are best recovered in batch or semi-continuous reactors, such as Knelson or Falcon BCCs (Klimpel, 1999), while smaller particles of free gold and unliberated gold particles associated with gangue are targeted for recovery in continuous units, such as flash flotation capable of producing the much higher mass yield in the form of a sulfide concentrate (Laplante and Gray, 2005).

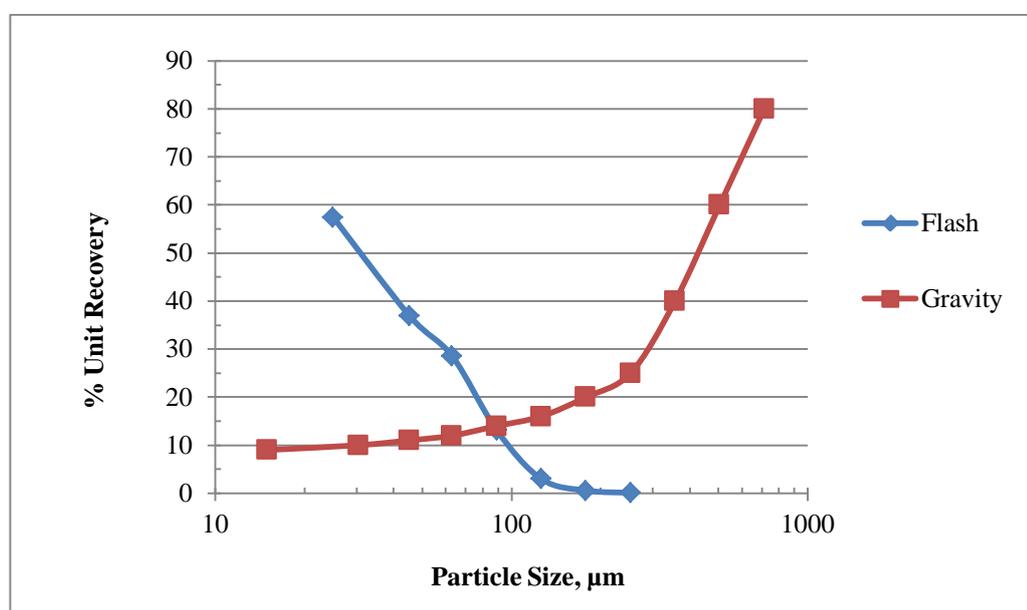


Figure 1-1. Comparative unit performance for recovery of GRG (Laplante and Dunne, 2002b)

Despite the increase in the application of flash flotation, which is generally targeted at sulfide recovery, the behaviour of all sizes of free gold within a flash flotation cell is poorly understood and consequently hard to predict (Dunne, 2005; Laplante and Dunne, 2002a). In the last decade, or so, some work on the behaviour of sulfides in flash flotation as well as descriptions of the hydrodynamic conditions existing within the cells has been published (Bourke, 2002; Lamberg and Bernal, 2009; MacKinnon, 2002; Newcombe et al., 2012a, b, c, 2013a; Warder and McQuie, 2005). The focus of this research is on free gold particles which demonstrate very

dynamic shape variations as they successively comminute within a milling circuit, as opposed to sulfide or silicate particles which yield little shape variation with progressing milling due to their brittle nature. Currently, there are no other studies focusing on the identification of factors which influence the recovery of free gold particles by flash flotation. Understanding the behaviour is even more complex when flash flotation and gravity recovery are both acting upon the circulating load of a closed loop milling circuit. Identifying the impact that changes in mineralogy, reagent use, operational/mechanical factors, and physical variables (such as size, shape, surface area, elemental composition, etc.) can have upon recovery will lead to an improved understanding of the behaviour of free gold being recovered within the milling circuit. This knowledge can then be used to make predictions about the gravity recoverable gold (GRG) and the Flash Recoverable Free Gold (FRFG) content of an ore and the likelihood of recovery of those components by gravity and flash flotation circuits.

The importance of the gravity/flash flotation relationship for free gold recovery was first identified by Dr. Andre Laplante of McGill University in Canada. Laplante spent many years developing a test (the GRG test) to characterise the GRG content of an ore and predict the gold recovery by BCC units with a GRG model. Laplante then explored the connection between gravity and flash flotation recovery in the milling circuit (Laplante and Dunne, 2002a). Before his untimely death, Laplante had proposed a combined gravity/flash flotation test (Laplante, 2005). This thesis endeavours to further the work of Laplante and provide theoretical explanations for trends observed in the recovery of free gold within the milling circuit by defining and characterising Flash Recoverable Free Gold (FRFG).

The following hypotheses for this study were developed through the literature review offered in Chapter 2:

- *A reliable and accurate laboratory test can be designed to quantify the Flash Recoverable Free Gold (FRFG) content of an ore akin to the gravity recoverable gold (GRG) test which has become the standard for*

characterising the GRG content of an ore. This test, along with supporting data from plant surveys, can be used to study the impact of various chemical, physical and operational parameters upon free gold recovery within a milling circuit.

- *The natural hydrophobicity and impact of collector addition on the performance of free gold in flotation is not consistent across the various size classes of interest and is also linked to gold genesis.*
- *Stereological inferences from traditional two dimensional microscopy measurements are unsuitable for characterising the shapes of free gold particles recovered in the milling circuit.*

1.1 Objectives

This work endeavours to elaborate on the fundamental knowledge of how selected chemical, physical and operational factors (or combination of factors) affect the behaviour of FRFG and thereby impact the chances of recovery in a combined flash flotation and BCC circuit by achieving the following objectives:

1. Develop a robust and repeatable bench scale flash flotation test (the Free Gold Flash Flotation Test) suited to determine the maximum free gold recovery. The free gold particles which are recovered in this test represent the ultimate FRFG content. The method will:
 - a. Be reproducible,
 - b. Distinguish free gold from gold in sulfide carriers,
 - c. Assess if the test can be conducted on dry plant samples, and

- d. Identify conditions which maximise FRFG recovery across the possible range of physical and chemical factors known to affect recovery of free gold in flotation. This type of information previously existed in an anecdotal form but will now be demonstrated with the laboratory testwork.
2. Investigate the response of free gold of differing genesis in key size classes (coarse, intermediate and fine) to changes in collector dosage.
3. Determine the recovery behaviour of free gold in an industrial plant setting with gravity and flash flotation operating in parallel, with an emphasis on the influence of size and shape.
4. Evaluate the accuracy of stereological measurements using current techniques for the quantification of free gold shape by comparing two and three dimensional (2D and 3D) methods and identifying of the limitations of these applications.

1.2 Scope

Review of available literature demonstrates that the behaviour of free gold in a flash flotation unit is poorly understood, especially when in competition with a gravity recovery unit. This is particularly so when flash flotation is used in conjunction with gravity recovery as, currently, there exists no definitive factors for which predictions can be made to understand and evaluate the impact of changes made to the process or the feed composition. Identifying the effect that changes in mineralogy, reagent use, operational/mechanical settings and other factors can have upon recovery will determine the factors that affect the performance of such circuits and will allow for an improved understanding of the behaviour of free gold recovery in the milling circuit.

While there is not a comprehensive understanding of free gold in flash flotation, Laplante and colleagues at McGill University, in collaboration with the Curtin AMIRA P420 Gold Technology Group, invested considerable effort in understanding the behaviour of free gold in gravity concentration applications. The

researchers defined gravity recoverable gold (GRG) as an important characteristic of gold ores and developed a model to predict recovery of GRG using BCCs based on laboratory performance in a three stage (and a simplified single stage) GRG test. Years of surveying and additional laboratory testing have created a reliable GRG recovery model which takes into account factors such as BCC efficiency and particle size to estimate plant recoveries. Previously, extrapolation of data from the GRG data has been the only way to predict GRG recovery by flash flotation. This method for prediction of free gold recovery has limitations because, although flash flotation is primarily expected to recover a different (finer) portion of GRG material than BCC units, it will compete with BCCs for intermediately sized free gold particles.

In this study, the Free Gold Flash Flotation test to determine FRFG content of an ore was developed and the effect of chemical factors (reagent addition) on the recovery of the FRFG material is evaluated in the literature as well as studied in the laboratory. The type and dosage of frother, activator and collector used for free gold flotation are compared in the literature as well as validated with laboratory testing. Additional reagents not tested in the laboratory (modifiers and depressants) are also reviewed in the literature.

The effect of airflow rate and agitation speed on the recovery of free gold are first evaluated in the literature and second with application of the Free Gold Flash Flotation test. A literature review was undertaken for other specific operational conditions such as hydrodynamics, gas mixing, rotor/stator types, vessel design (specifically dual outlet), pulp density, slurry pH, residence and conditioning times, and feed type.

In order to explore the differences in flotation recovery by size and genesis, samples made of a synthetic ore containing GRG and pure gold were subjected to the Free Gold Flash Flotation test with varying levels of the selected collector, potassium amyl xanthate (PAX). The flash flotation concentrate and tails were sized into coarse, intermediate and fine fractions to for ultimate recovery and kinetic studies.

The physical particle parameters which impact the recovery of free gold in a milling circuit are identified and discussed in the literature review. The parameters of interest include roughness, liberation, size, elemental composition, riming, shape, milling effects, natural hydrophobicity, surface coatings and kinetics. Often such physical parameters have a close relationship to each other and this research will demonstrate just how hard it is to independently determine their individual impacts. Samples were taken from surveys around the gravity and flash flotation circuits at three concentrators (Tongon, Telfer and Kanowna Belle) with a parallel BCC and flash flotation arrangement. The samples were sized into coarse, intermediate and fine fractions in order to conclude if size and shape as determined by common 2D (QEMSCAN) and 3D (Micro CT) methods have an impact upon free gold recovery in a milling circuit.

1.3 Overview

The literature review in Chapter 2 of this thesis focuses on the knowledge held within industry and academia on both flotation and gravity concentration. When possible, the comments are directed specifically to the flash flotation and BCC concentration units. Most literature on flotation, specifically flash flotation, exists for sulfide based systems, not free gold or GRG as is the focus of this research. The review attempts to link conventional flotation of free gold knowledge to the application of flash flotation. As already identified, many gaps exist in the understanding of the behaviour of free gold in flash flotation. These gaps are highlighted in the literature and, when possible, have been researched within the scope of the project.

Chapter 3 gives the methods for the experimental chapters.

Chapter 4 details the development of the Free Gold Flash Flotation test. This test serves to characterise the maximum FRFG content of an ore and is suited to a variety of different ores with minimal (and defined) variation in the results. While the sample size for this testwork is small and there is an inherent problem with the nugget effect (the result of gold particles not being evenly disseminated throughout a

low concentration ore which leads to erroneous assay results), discussion and understanding of these limitations allows for continued application of the Free Gold Flash Flotation test to quantify the FRFG content of an ore. Three kinetic models are evaluated for best fit to the data.

In Chapter 5, the Free Gold Flash Flotation test is employed to investigate flotation recoveries of synthetic ore containing gold of varying genesis; milled gold particles from a laboratory BCC concentrate of mixed origin and synthetically manufactured pure gold samples purchased from Sigma Aldrich. Kinetic data from the testwork reveal the types of particles suited to flash flotation, as well as conventional flotation circuits, with insight into natural hydrophobicity, residence time, particle size, elemental contamination and the effect of milling.

Chapter 6 details the characterisation of the free gold content from samples obtained by surveys conducted at three industrial plants. Samples were investigated for trends in size, shape, degree of liberation and elemental composition as they affect the recovery of the contained free gold. The characterisation primarily focuses on concentrate samples from both flash flotation and gravity to help determine which factors influence preferential deportment of free gold. Intermediate size fractions of each sample were analyzed by 2D and 3D imaging methods, with some pre-concentration required to increase the gold grade and likelihood of imaging the particles of interest. Contradictory results emphasize the need to develop an applicable technique to determine free gold shape and importance of stable plant operation for flash flotation and highlight the benefit of parallel flash flotation and gravity circuit configurations for some operations.

Chapter 7 offers conclusions for the experimental chapters and makes recommendations for future work.

CHAPTER 2. LITERATURE REVIEW

This literature review will focus on free gold occurrences, current and past processing methods, the gravity and flash flotation relationship, factors that influence recovery and methods for particle characterisation.

2.1 Gold Occurrences

2.1.1 Gold Deposit Formation

Gold deposits may form in many geological environments, such as magma chambers, ancient volcanoes and hot springs, or conglomerates and sandstones. However, gold is most commonly found along ancient fault zones in deposits resulting from the erosion of gold bearing rocks. According to the Department of Earth Science and Engineering at Imperial College London (2011), more than 2.5 billion years ago, during the Archaean period, early Earth experienced a phase of intense metamorphism and intrusion of igneous rock. During this era, earthquakes along fault lines released hydrothermal solutions from deep in the Earth's crust. That hot, salty fluid, containing dissolved gold which had been extracted from the hot rocks, found the path of least resistance leading toward the Earth's surface. Under the cooler conditions at the surface, the gold became insoluble and precipitated out into veins of quartz. This type of gold/quartz association, which is most common, is termed a "primary gold deposit".

The following list notes the six main types of gold deposits that are broadly used when discussing gold ores, according to Vaughan (2013). All listed types are primary ores and therefore oxide ores (as oxide ores are associated with all primary ore types) and within each type there are sub-types, which have not been elaborated upon in this text. The presumed association with free gold is noted, although no references were found in which any group has studied and documents the free gold related to each deposit in depth.

1. Oxide – all free milling with free gold occurring,

2. Orogenic - mostly free milling; free gold common,
3. Epithermal – both refractory and free milling; some free gold,
4. Witwatersrand – free milling; some deposits of native gold,
5. Carlin type – refractory and preg-robbing; little or no free gold, and
6. Copper-gold:
 - Au rich porphyry Cu – some free gold at times,
 - Iron oxide copper-gold (IOCG) – some free gold and uranium at times.

Two other minor types of gold deposits are volcanogenic massive sulfide and gold skarn, each offer a minor source of gold compared to the six main groups previously listed. Volcanogenic massive sulfide (VMS) deposits are a major class of Cu-Pb-Zn orebodies, producing a large percentage of the world's Cu, Pb and Zn. Some VMS deposits contain gold, which can be extracted as a by-product. Skarn refers to a generally small orebody in which igneous rock such as granite has intruded limestone (CaCO_3). There are different types of skarns, such as copper, tin, gold, etc. Gold skarns, where gold is the major metal produced, are a relatively minor source of gold.

2.1.2 Types of Gold Associations

Sometimes, chemical degradation and mechanical factors, such as weather, erode the host rock, quartz, and expose the veins of gold in the primary ore deposit. After physical breakdown of the quartz, the liberated dense gold is concentrated in the soil or nearby waterways. This secondary type of occurrence is known as an alluvial or placer deposit. Gold was first discovered by humans as shiny yellow flakes and nuggets of free (native) gold in alluvial deposits in rivers or streams. Other forms of gold, such as microscopic particles or those bound in a sulfide matrix, were not detected until later.

The average gold concentration in the Earth's crust has been estimated at only 2 to 5 ppb by some authors (Klimpel, 1999; Marsden and House, 2006), while others suggest the average is only 3 ppb (O'Connor and Dunne, 1994). Gold is not

evenly disseminated throughout the crust but rather mined from small pockets with a higher grade, warranting extraction. Gold may exist in a native form, also referred to as free or liberated when located within a comminution circuit. Often, gold can be bound or associated with gangue minerals such as oxides and, most frequently, sulfides. Gold associations with gangue components are important as they affect a particle's ease of recovery, for example clays can increase the slurry viscosity and decrease the sharpness of a gravity separation while oxide or sulfide coatings can affect a particle's floatability. Common gold associations with sulfide minerals are described by (Marsden and House, 2006), the most general are illustrated in Figure 2-1.

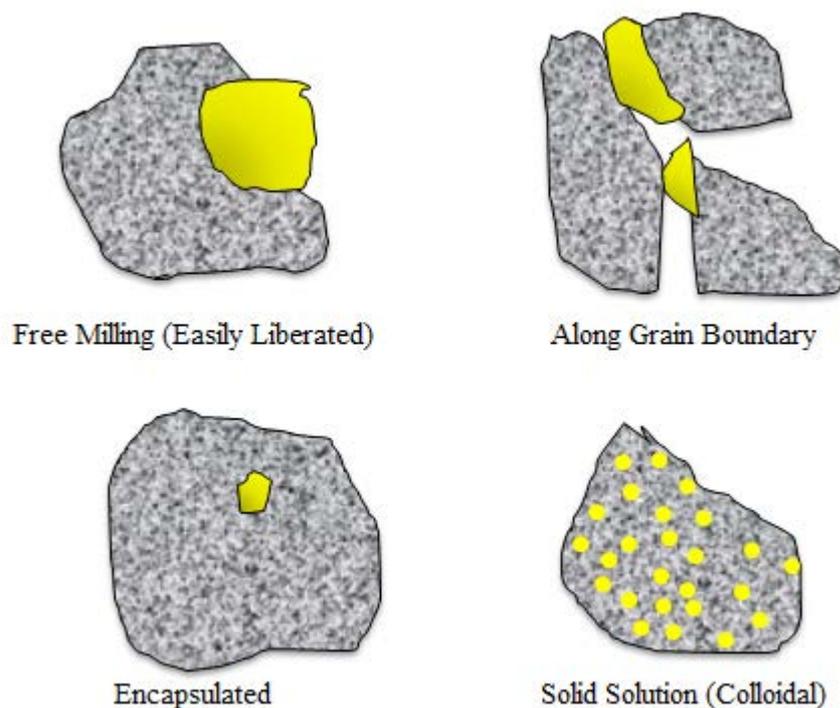


Figure 2-1. Typical gold (yellow) associations with sulfide minerals (grey)

According to Marsden and House (2006), copper and gold were the first metals of interest to humans partly because of their native occurrence and partially due to their malleable and ductile nature. Free gold can occur in a variety of physical forms. In large quartz reefs, fine gold can occur as disseminated particles, irregular

grains, scales, plates, or veins (Birch, 2011). Coarse gold may take the form of large, compact slugs or spongy masses. Nonetheless, all gold has the same octahedron crystal structure and physical properties. Due to the similar atomic structures of gold and silver, it is also common for the two metals to occur as natural alloys (called electrum), in fact, 100 % pure gold is rarely found in nature (Marsden and House, 2006). Gold and electrum can also contain a portion of copper, with the percentage varying in each deposit.

2.1.3 Gold Mineralogy

Although not often thought of as a complex element in chemical systems, the mineralogy of gold is quite multifaceted. According to Vaughan (2004), the principal gold minerals which influence the processing of gold ores are native gold, electrum, Au-Ag tellurides, aurostibite, maldonite and auricupride. Additionally, solid solution (submicroscopic) gold found in arsenopyrite and pyrite can be important. The minerals in which gold is a major constituent are shown in the upper section of Table 2-1, where the bottom portion shows common minerals with gold present as a trace or minor element.

Table 2-1. Gold mineralogy (Vaughan, 2004)

Gold Minerals		
<u>Mineral</u>	<u>Composition</u>	
Native gold	Au	
Electrum	(Au, Ag) (20-50 % Ag)	
Calaverite	AuTe ₂	
Krennerite	(Au, Ag)Te ₂	
Sylvanite	AuAgTe ₄	
Petzite	Ag ₃ AuTe ₂	
Aurostibite	AuSb ₂	
Maldonite	Au ₂ Bi	
Auricupride	AuCu ₃	
Common Minerals with Trace Levels of Gold		
<u>Mineral</u>	<u>Composition</u>	<u>Au Concentration</u>
Arsenopyrite	FeAsS	<0.3 ppm-1.7 wt %
Loellingite	FeAs ₂	1.5-1087 ppm
Pyrite	FeS ₂	<0.25-800(?) ppm
Terahedrite	Cu ₁₂ As ₄ S ₁₃	<0.25-59 ppm
Pyrrhotite	Fe _{1-x} S	0.006-1.8 ppm
Marcasite	FeS ₂	0.05-4.1 ppm
Chalcopyrite	CuFeS	0.01-20 ppm

2.1.4 Gold Properties and Uses

Gold has the symbol Au, from aurum, the Latin word for gold. It is the only yellow metal. Pure gold is the brightest yellow, while alloys containing silver, rhodium, palladium or iridium will not only increase hardness but also increase “whiteness”. Blends containing copper can be rose or green tinted, see Figure 2-2.

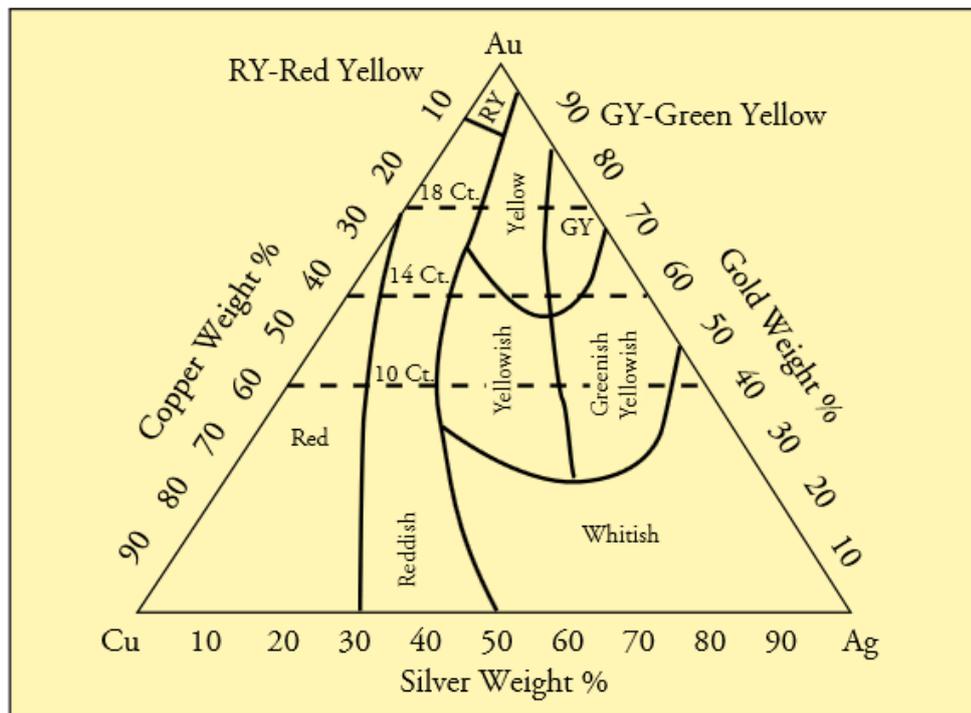


Figure 2-2. Ternary plot of Au-Ag-Cu alloy colours (Cretu and van der Lingen, 1999)

In addition to being a good conductor of heat and electricity, gold is also quite malleable and of high density. The density of gold and its alloys with copper and silver have been calculated and experimentally summarised by Kraut and Stern (2000) in Figure 2-3.

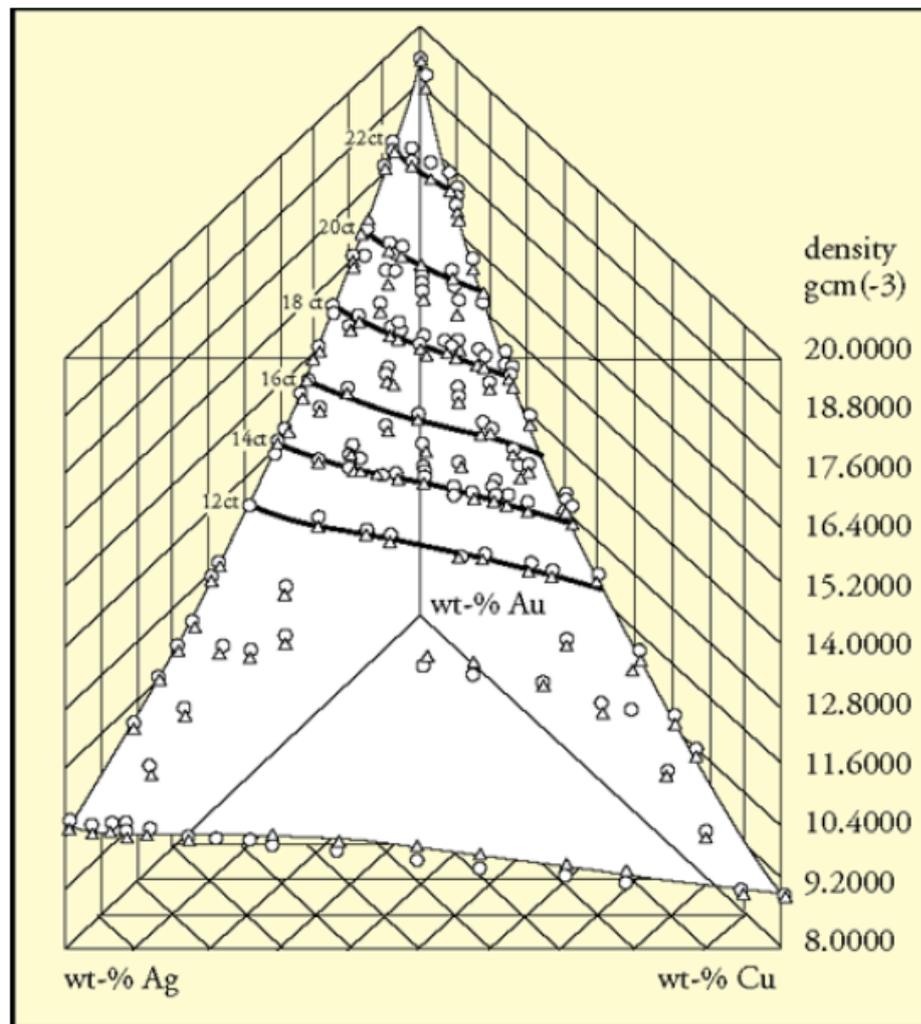


Figure 2-3. Ternary plot of Au-Ag-Cu alloy densities (Kraut and Stern, 2000)

Gold is also unique in its ability to resist corrosion by most acids, which is why it is described as inert or noble. Usually, dissolution of gold is performed by either a strong mix of nitric and hydrochloric acids called “aqua regia” or an oxidising ligand system; for example an oxygenated alkaline cyanide solution. The properties that make gold very stable have given rise to its popularity for craft, worship, trade and technology over many thousands of years in human history. Figure 2-4 shows the international demand for gold, by industry type from 2012 data.

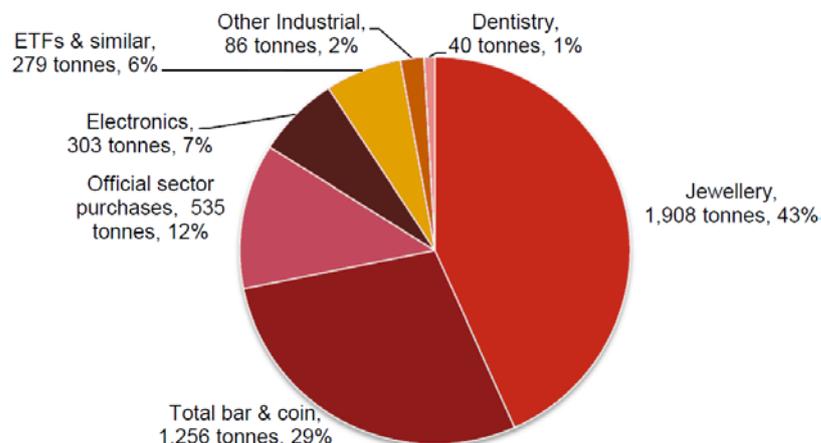


Figure 2-4. Global gold demand (PWC, 2013)

There has been a shift in the global gold demand that has taken place compared to some statistics reported six years earlier – in 2006, about 60% of gold production was used in jewellery and another 20% was kept in reserves, while the remaining 20% of the gold supply feed industry sectors (Marsden and House, 2006) including computer circuitry, cosmic ray protection for spacecraft and satellites, telephones, telescopes, photocopiers, thermometers, nightsights and security cameras, dentistry, eye surgery, arthritis treatment, aircraft engines and windows, heat reflecting visors, and more (Imperial College London, 2011). It was estimated that all the refined gold ever produced (up to 2006) would fill a 20 m cube, from an average head grade of about 6 g/t, from a 100 km x 100 km x 1m block from which it had been mined (Marsden and House, 2006).

2.2 The Evolution of Gold Processing

2.2.1 Pre-Cyanidation (pre-1888)

The history of gold processing, as described by Marsden and House (2006) and Habashi (2005) begins around the Neolithic age (4000 BC to 2200 BC), where people in the Middle East collected alluvial gold from streambeds and eventually developed crude gravity concentration methods. Around 1300 BC miners in Nubia

(now Sudan) began following a shallow underground vein, processing by manual sorting and a variety of gravity concentration methods (Habashi, 2005). Gold grains and bars became a form of monetary payment, followed by its use as decoration and jewellery. Egyptians began alloying gold and silver around 500 BC, but pure gold coins were not minted until 560 BC (Marsden and House, 2006).

The Roman Empire needed great quantities of mineral wealth to fund their exploitations, which catalysed another set of technological advances. The Romans began sluicing, while the Spanish developed hydraulic mining, i.e. water wheels and the Archimedean screw. Many mining schools were created and thrived during this period in Europe; though the work force was made of slaves experiencing a high, job-related, mortality rate. Gold production decreased with the fall of the Roman Empire.

In 1400 AD, central Europe had a mining resurgence with amalgamation and retorting as the new technologies (Marsden and House, 2006). In the 16th century, Georgius Agricola published *De Re Metallica* (Agricola, 1556), depicting metallurgical practice in the Germany during this period. As deposits in South America and Mexico were exploited, gold production plummeted in Europe. The gold rushes of the early 19th century began with the discovery of alluvial deposits in Siberia, where primitive gravity concentration was used to capture the native gold (Marsden and House, 2006). The methods evolved from panning to water powered trommels and strakes. Gold rushes soon encompassed the Americas, Australia, New Zealand and South Africa. Processing evolved from rudimentary gravity concentration to cradles, long toms, rockers and screening. As the alluvial sources were quickly expended, workers began pursuing quartz veins and underground gold mining rapidly developed.

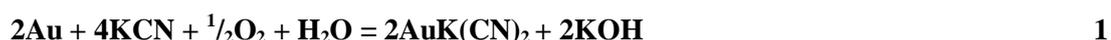
The ancient techniques of gravity and amalgamation were unsuitable for recovery of the bulk of the gold material in the new types of ore being exploited. Gold was now found to be occurring in fine particles and often associated with sulfides. Hydrometallurgists developed chlorination (passing chlorine gas over crushed ore to produce a gold-chloride complex which is water soluble) to treat

sulfide ores and lower grade gravity concentrates. Due to chlorine's toxicity, other chemicals, including bromine, thiosulfate, thiourea and cyanide, were evaluated in the early 1900s for their gold dissolving properties (Marsden and House, 2006).

Pyrometallurgy in the 19th century evolved from amalgamation and retorting to creating high grade concentrates by direct fusion in a lead bath, direct smelting with lead rich fluxes and smelting with fluxes to produce a matte followed by resmelting with lead-rich fluxes (Habashi, 2005; Marsden and House, 2006). In the mid to late 1800s a combined roasting-smelting process for pyritic gold ore was employed in the United States to degrade the host gangue material and gain access to the contained gold particles (Marsden and House, 2006). Eventually, roasters were employed across the Americas and Australia to oxidise ores and concentrates prior to chloride leaching.

2.2.2 Cyanidation (1889-1971)

The cyanidation process, as shown in the following Equation 1, was developed in 1887 and 1888 by McArthur and the Forrest Brothers (Marsden and House, 2006).



The process was first put into production at the Crown Mine in New Zealand, 1889 (Marsden and House, 2006). The development of the cyanidation technique allowed low grade ores made of fine grain gold to be processed economically and thus it quickly spread across the world.

In the early 20th century, a typical gold plant processing flowsheet included crushing, screening, manual sorting of waste rock, stamp milling, amalgamation, cyanide leaching, dewatering, zinc precipitation (Merrill-Crowe) and electrolytic cell recovery. In the 1950s, the Carlton mine in Colorado was the first to use activated carbon, in place of zinc precipitation in a modern industrial situation (Marsden and House, 2006). Although the use of carbon to capture the gold in solution had been known since the late 1800s, it was unable to economically compete with the Merrill-

Crowe process until regeneration and elution methods increased the extraction efficiency (Habashi, 2005).

2.2.3 Modern Technological Developments (1972- present)

Over much of the past four decades, a rise in metallurgical and processing technology has been observed. Chemical process such as carbon-in-leach (CIL), carbon-in-pulp (CIP), biological oxidation, pressure oxidation, heap and dump leaching of low-grade ores and intensive cyanidation have become widely used in industry. Innovations in ancillary processes, such as carbon regeneration, reactor design and process control, have also played an important role in gold extraction of the recent era. The industry is presently looking into unconventional gold leaching systems, including alternative lixivants, resin-in-pulp (RIP), and whole ore oxidation in pilot and large scale operations to treat low grade ores and reduce or eliminate the use of cyanide.

Many complex ores being processed today are not readily amenable to direct cyanidation either for economic or technical reasons. Future gold recovery will need to find ways to best process these ores while meeting production requirements, abiding by strict environmental compliances, and minimising energy and reagent costs. The modern trend has been, and will continue to be, the treatment of lower grade ores with more complex mineralogy, while maintaining environmental compliance and reducing power consumption. Emphases in future research will likely include a continued search for the ideal non-cyanide gold leaching system (i.e. fit-for-purpose lixivants), gold recovery from scrap, improved process analysis and control, minimising water consumption, improved characterisation and mineralogical diagnostics, innovative use of flotation in flowsheets and alternative methods for upgrading gravity concentrates.

The use of gravity recovery and flash flotation operations in a closed loop milling circuit has been identified as an option for processing complex ores containing both free gold and gold in a sulfide matrix. In such cases, and as in the configurations studied in this thesis, a modern gravity circuit can be used to recover

the larger, coarse particles of free gold, via batch or semi-continuous reactors, such as Knelson or Falcon BCCs. The fine free gold and unliberated gold particles in gangue are targeted for recovery within the milling circuit by continuous units, i.e. flotation, capable of producing the much higher yield required to form a sulfide concentrate (Laplante and Gray, 2005). In this arrangement, the grade and composition of concentrate and the types of gold captured in each concentrate differ. For example, Gül et al.(2012) concentrated a gold ore with a 6 g/t head grade by both gravity and flotation. The reported gravity yield was at 620 g/t (41.4 wt %) and flotation yield at 82 g/t (89.9 wt %) though the mass of concentrate produced is much larger in the case of flotation.

2.3 Gravity Concentration

2.3.1 Development of Gold Ore Concentration

Throughout most of the history of mineral processing, gravity separation methods have been used to treat a wide variety of ores, from sulfides to coal, and especially those ores which contain coarse free gold. Traditionally, gravity recovery equipment ranged from sluices (the most simple form of a gravity concentrator), to Reichert cones and spirals, on to jigs and Wilfley or Gemeni tables (Wills, 2006). Despite the rise in the use of cyanide for gold recovery, gravity techniques remained strong in the first half of the twentieth century and are still being used today to recover gold in the grinding circuit (Laplante and Staunton, 2003). However the use of gravity methods for many ores declined in the early 20th century with the advent of flotation. In the last 40 years concerns over environmental factors and flotation reagent cost have reignited interest in gravity recovery. Recently, there has been a resurgence in the use of gravity with the advent of centrifugal concentrators, such as Knudsen bowl, Knelson, Flacon, Kelsey Jig and Mozely, which have led to improved treatment of ores containing free gold (Koppalkar, 2009).

2.3.2 Principles of Gravity Concentration

Efficient gravity concentration methods separate materials based on a particle's response to gravity (centrifugal force in the case of the BCCs, used as a specific example due to their popularity as the most commonly used gravity recovery unit in use today) and the movement of a viscous fluid, usually, water (Koppalkar, 2009; Wills, 2006). The separation mechanism for all BCC units is fundamentally the same, the centrifugal force applied to the gold (and gangue) material needs to be great enough to embed the gold particle in the fluidised bed (concentrate) area of the riffles, as illustrated in Figure 2-5. Therefore, a greater difference in density between the valuable material and the gangue will yield a better separation of the tailings from the concentrate, making free gold a prime candidate for gravity recovery methods.

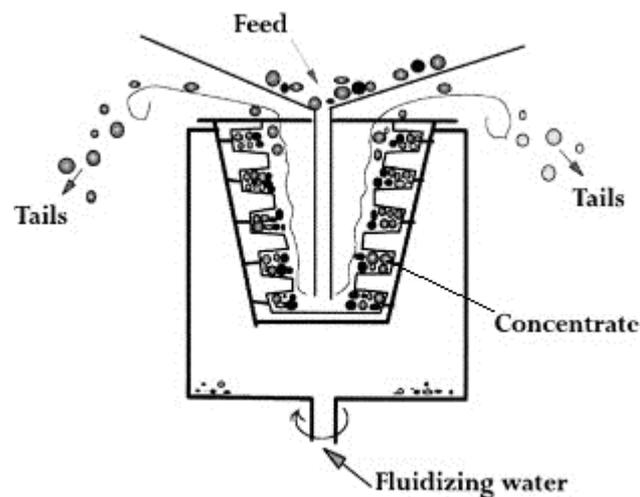


Figure 2-5. Knelson diagram (Coulter and Subasinghe, 2005), permission granted by Elsevier

The effect of particle interactions and drag must be considered in the explanation of BCC operation. Bridgwater et al. (1983) describes the mechanism of recovery in a Falcon concentrator as particle migration or percolation. They suggest, in the case of dry, cohesionless particles, a particle smaller than the bed will have a

harder time entering the bed and the motion of large particles through an array of small particles is called migration. For bulk materials in a fluid, bed packing occurs in a similar mechanism referred to as percolation. Huang (1996) labelled the combination of centrifugal force, shear induced dispersive forces and fluidisation water in a Knelson concentrator as interstitial trickling, which can be compared to percolation.

2.3.3 Factors Affecting Gravity Performance

In general, when the GRG content is high and the size fraction is coarse, free gold is easy to recover and concentrate in gravity operations. However, the ability of free gold to be recovered or become a part of the circulating load in a mill with a gravity circuit is heavily dependent on the particle's size, density and, possibly, shape.

Due to the large density difference between particles of free gold and gangue, and the grind resistance of gold, the gold particles will remain in the recirculating load for longer until it has been ground fine enough to be removed in the cyclone overflow or, unless, it can be removed earlier, by gravity or flash flotation within the milling circuit as preferred. For example, while the sulfide recirculating load in a milling circuit may generally be around 200% it is not uncommon to find gold recirculating loads at 1000% or 1500%. Previous studies (Banisi et al., 1991) have demonstrated the effect of hydrocyclones upon the gold content in the recirculating load and Figure 2-6 illustrates the differences with a typical partition curve for ore and GRG exemplifying the significant difference between the two.

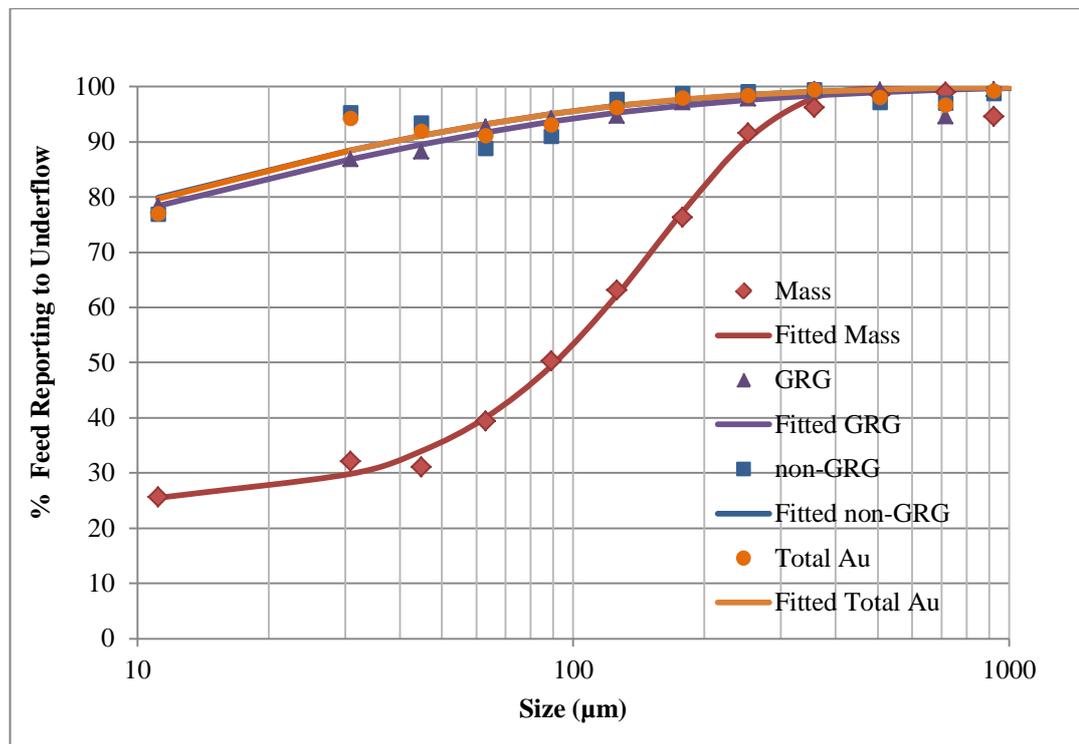


Figure 2-6. Typical ore, gold and GRG partition curve (Wardell-Johnson and Bax, 2012a)

Gold is malleable, not brittle like most gangue and sulfide minerals so not only does gold grind six to 20 times slower than the gangue, but it may become flattened and is then subject to report to coarser size fractions (Grewal et al., 2009) giving further cause for retention in the milling circuit.

2.3.4 Retention of Free Gold in the Milling Circuit

Build-up of free gold in the milling circuit occurs due to its high density in addition to malleability in comparison to gangue material. Free gold much smaller than the intended cut size (20 µm vs. 57µm) will report to the cyclone underflow and be retained in the milling circuit until it has been sufficiently reduced to report to cyclone underflow (Banisi et al., 1991). However, gold is malleable, and does not comminute well, so it can take 50-100 passes through the milling circuit until free gold reports to the downstream process (Laplante, 2000). The use of BCCs and flash flotation operations in a closed loop milling circuit is one option for reducing the

circulating load of free gold and processing complex ores containing both liberated (or free) gold as well as gold in a sulfide matrix (unliberated or refractory). In such cases, gravity circuits can be used to recover the larger particles of free gold (+106 μm), while a flash flotation circuit will produce a sulfide concentrate including smaller free gold particles (-106 μm) and gold contained in sulfides.

Two important, but not well understood, factors in the response of a gold particle to concentration efforts by gravity or flotation devices are shape and hydrophobicity which have both been suggested to impact the potential for recovery in the milling circuit (Laplante and Gray, 2005). While reagent additions are used to modify hydrophobicity the effect of shape in gravity and flotation recovery units can best explained by examining the principles regarding settling.

2.4 Settling

2.4.1 Ideal Settling

In a simplified slurry system, spherical gold particles settle quickly while, in comparison, flat particles of similar mass stay suspended in solution longer due to increased drag. Therefore settling and the hydrodynamic forces that impact the behaviour of free gold particles in a milling circuit are important to both gravity and flotation processes. Wills (2006) describes free settling as particles sinking in a volume of fluid which is large in comparison to the volume of particles. When a particle is free settling in a vacuum, the particle is subject to constant acceleration and its velocity will increase indefinitely, regardless of size or density. In this instance, a nugget of gold and a lump of ore would fall at the exact same rate. Wills goes on to clarify this is not the case for settling in most instances. Rather, in a viscous medium, such as air or water, a particle is subjected to three forces; gravitational force, drag and buoyancy. When the forces have reached equilibrium, the particle will fall at a uniform rate called terminal velocity. At low velocities, the main cause of resistance to settling is due to shear or the movement of the water around the particle's surface, known as viscous resistance. At high velocities, the

primary source of resistance to settling is due to the displacement of fluid in the path of the particle, known as turbulent resistance. In this way, the overflow of a classifier, such as a cyclone, will contain particles with terminal velocities lower than that of the fluid while the underflow will be comprised of particles with terminal velocities higher than the rising velocity (Wills, 2006).

Two equations are used to describe free settling of particles in a particular fluid; Stokes' law (Equation 2) for particles smaller than 50 μm and Newton's law (Equation 3) for particles greater than 0.5 cm, noting an intermediate size range exists for which neither law fits to describe the experimental data.

Stokes' law is given as:

$$v = k_1 d^2 (D_s - D_f) \quad 2$$

And Newton's law is given as:

$$v = k_2 [d(D_s - D_f)]^{1/2} \quad 3$$

Where:

v = terminal velocity,

k_1 and k_2 = constants,

d = particle diameter,

D_s = particle density,

D_f = fluid density.

Examination of the two laws reveals that if two particles have the same density then the particle with the larger diameter has the higher terminal velocity and if two particles have the same diameter then the heavier particle has the higher terminal velocity. Further examination of these laws reveals that the density difference between particles has a greater effect on classification at a coarser size

range (Wills, 2006), as is the case with BCCs. However, once the particles enter the hindered settling conditions (pulp density above 15 %) or deviate from an ideal sphere, the settling behaviour changes.

2.4.2 Hindered Settling

In hindered settling conditions, the high density and viscosity of the pulp create a turbulent resistance through which the particle falls. As such, the result of hindered settling is a reduction in the effect of size and an increase in the effect of density on separations (Wills, 2006). Gravity separations are more effective with increasing density differences between the target material and the gangue. In BCC circuits, it is critical to properly screen the feed material to provide ideally sized particles and make best use of this principle. A problem arises on site as the sharpness of separations is influenced by time, surface area and water addition, which often means achieving the ideal feed material is too expensive or intensive to manage. Often, BCC units will be underfed or fed incorrectly sized material due to the tight screening constraints of providing optimal feed material.

The effect of shape on non-spherical particles is often described by circularity (2D) or sphericity (3D), which are essentially factors that describe a particle's deviation from an ideal circle or sphere. Rhodes (2008) claims that shape affects the force of drag greater in the non-Stokes law region, that is for particles greater than 50 μm , which is why it is of interest in BCC and flash flotation recovery. It is also stated that, in the Stokes law region, particles fall with their longest surface parallel to the direction of fluid motion while particle in the region of Newton's law present their maximum area to the oncoming fluid (Rhodes, 2008). Interestingly, no claim is made about particle presentation in the intermediate range, which is of interest to both the gravity and flash flotation applications.

2.5 Gravity Recoverable Gold

While BCC units have been shown to best concentrate coarse free gold particles, ideally, larger than 106 μm , some recovery of particles between 106 and 37

μm is attained, where recovery may be particle shape dependent within this range. BCC systems are incapable demonstrating consistent recovery of gold particles smaller than $37 \mu\text{m}$ (Laplante and Dunne, 2002a). Operational and mechanical factors, such as solids density and feed rate of the incoming stream, as well as fluidising water pressure and condition of the bowl liner must also be considered to optimise recovery and achieve maximum individual unit performance. The test for determining GRG content and gravity recovery amenability are discussed in more detail in this section.

Gravity recoverable gold, or GRG, is a specific term which refers to gold reporting to the concentrate stream with a small mass yield if separations are performed using BCCs. Recovery of GRG usually forms a low weight concentrate, with typically $<0.1\%$ mass pull, by a BCC units (Laplante and Gray, 2005). This gold is primarily in the form of liberated or free gold. Gold particles associated with sulfides, known as gold carriers, typically will not report to the concentrate in GRG recovery because the apparent particle density is lower than that of free gold. Sulfides do report to the BCC concentrate but not as selectively as gold, and the low mass pull limits the percentage of sulfide that can be recovered. Partially liberated gold must have a high SG (over 14) to routinely report to the GRG concentrate stream (Laplante and Gray, 2005; Staunton, 2011). This is why GRG, by definition, is comprised of free gold. While a simple ore will produce a GRG concentrate as feed for cyanidation or smelting processes, concentrates of more complex ores may require further upgrades or processing.

Laplante and Xiao (2001) identified three approaches to determine the amenability of an ore to gravity concentration. The most comprehensive and costly approach is to commission a large scale pilot plant. In this scenario, the new equipment will have gold traps which will affect the results until a large tonnage has been processed. While this might yield the most reliable results in the long term, the system takes some time and dedication to equilibrate. Secondly, of midrange cost, an operating plant may decide to conduct in-plant testing by retrofitting the existing circuit. Lastly, new and operating concentrators may decide to commission

laboratory GRG test program at modest cost, which will be described in the next paragraph. Unfortunately, the small sample size will make it difficult to obtain a representative sample as is the case for much of the testwork regarding free gold ores. This issue, referred to as the “nugget effect” is a result of gold particles not being evenly disseminated throughout a low grade ore, as well as partitioning effects caused by gold’s large density. Additionally, data reproducibility, the transient response of the system and overgrinding can further complicate the issues.

Determination of an ore’s GRG content by means of a laboratory testwork campaign is not a simple exercise. Researchers from McGill University in Montreal, headed by Dr. Andre Laplante, created a test to determine GRG content based on grind size, sequential liberation and partial recoveries. Recovery of GRG is function of three components; ore characteristics, grinding circuit (kinetics and classification) and gravity circuit (sized primary and secondary recoveries) (Laplante and Gray, 2005). The test uses a laboratory BCC concentrator to recover gold in series at three consecutive grind sizes (known as ‘Stages’) of P₁₀₀ 850 μm , P₄₅₋₅₅ 75 μm and P₈₀ 75 μm , as shown in Figure 2-7.

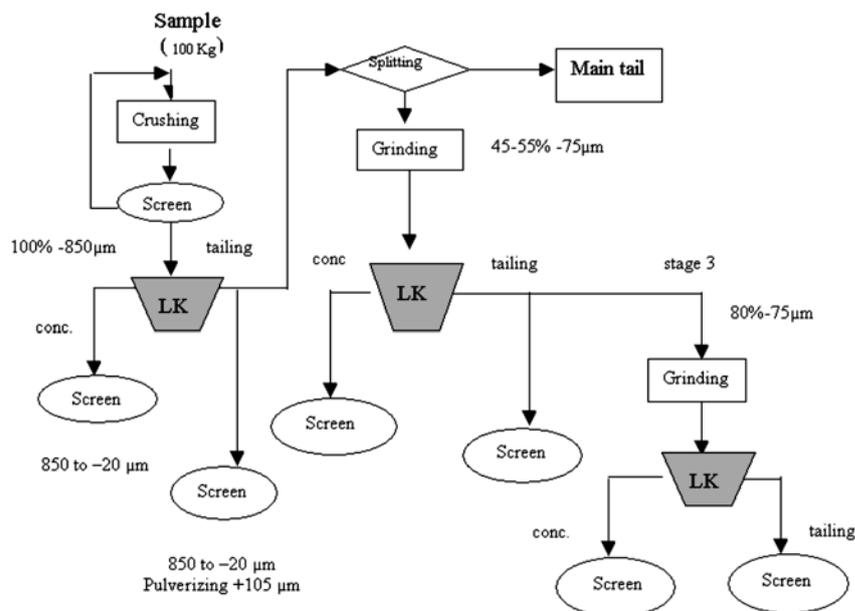


Figure 2-7. The GRG test procedure (Koppalkar, 2009; Laplante and Xiao, 2001)

Two condensed versions, a single stage (for ore) and “stream” (for a plant process stream) GRG tests, can also be used to characterise the GRG content. The various versions of the laboratory GRG test (three stage, single stage and stream GRG) can be used in design and optimisation phases. For example, geological samples subjected to a single stage or three stage GRG test would provide designers with important information about the GRG content of an ore and possible process design in green-fields (undeveloped) projects. All three of the tests can also be performed in brown-fields applications to learn more about the impact of changing ore types, classification and allow modification to the gravity circuit in order to optimise gold recovery at individual mills by means of the GRG model.

2.5.1 Available Gravity Concentration Technology

BCCs are best suited to treatment of a small portion of material, in applications of roughing, scavenging and cleaning (Koppalkar, 2009). The Knelson and Falcon concentrators are of particular importance because they have become the most popular of the centrifugal gravity concentrators due to their ease of operation, small capital cost, ability to be sized correctly for the application and use for recovery of commodities other than gold (i.e. platinum group metals). Many operations worldwide use other gravity concentration technologies such as jigs and spirals, but further discussion of non-BCC gravity equipment is beyond the scope of this review.

2.5.2 Advantages of Gravity Concentration for Free Gold Recovery

Implementation of a gravity recovery unit in a grinding circuit offers several benefits. Firstly, notwithstanding the capital investment (screens, magnets, structural modifications), it is relatively inexpensive both in terms of capital and operational costs and a high recovery can be obtained by low stage efficiency. The reagent use and power costs are decreased for the entire plant because gold reporting to the concentrate stream at the beginning of an operation will yield more profit than recovering further downstream in more expensive unit operations (i.e. cyanidation, leaching and carbon). Secondly, gravity units may increase overall recovery by

removing coarse gold particles which would not have enough residence time to fully leach in the case of coarse grind products or circuit upsets. However, it is important to not over emphasise the slow kinetics of large gold grains in leaching, as most coarse and intermediate particles will recirculate through the mill as a function of classification (Laplante and Staunton, 2003). Thirdly, having a gravity recovery unit fed by cyclone underflow takes advantage of an unintended, but advantageous, preconcentration step where hydrocyclones act as a rougher concentrator, sometimes concentrating gold up to 100 times (Mosher, 2005).

On average, gold particles larger than 75 μm will circulate 50-100 times in a grinding circuit before reporting to the concentrate (Laplante and Gray, 2005). The high circulating load of gold in the closed loop grinding circuit is attributed to the ductile, malleable nature of the element. Each trip through the mill changes the size/shape dependent response to process conditions. Instead of breaking up, the free gold grains initially become flattened flakes, effectively decreasing the opportunity for the gold to report to the concentrate stream of a gravity circuit (Banisi et al., 1991; Chryssoulis and McMullen, 2005). Since not all coarse GRG is recovered in a single pass through the milling circuit, it will eventually be slowly ground into finer particles. It has been suggested that between 75 and 90% of ground gold product is still gravity recoverable as the particle size tends to drop by only one size fraction at a time (Staunton, 2011). Because of the ample opportunity for recovery in this type of circuit, on average, only 10-25% of the circulating load is diverted to gravity treatment (Ryan et al., 2005). Table 2-2 summarises the benefits of gravity recovery ahead of cyanidation.

Table 2-2. Benefits of gravity recovery ahead of cyanidation (Laplante and Staunton, 2003)

Benefit	Comment
Coarse gold that has not enough retention time for cyanidation is recovered early	Poor classification with hydrocyclones minimises this benefit
	Coarse classification and low retention times in cyanidation circuits augment it
Gold particles with "passivated" surfaces that cyanide slowly or not at all can be recovered	Phenomenon quite common with oxidised ores
	Typically identified when free gold is found in cyanidation tailings, or when repulped tailings yield a measurable content of cyanidable gold
Dissolved gold losses are minimised	More important with Merrill-Crowe or when carbon fouling occurs
Less gold settles out in the circuit: the static gold inventory is minimised	Important advantage which is generally poorly documented
Carbon costs decreased	Attrition/breakage of carbon minimised
Head grade spikes smoothed out	Higher head grade often corresponds to coarser gold that can easily be recovered by gravity

Coarse free gold and some complex gold sulfide minerals can complicate cyanidation, so it may be advantageous to recover them with a BCC (free gold) or jig (sulfides and free gold) for further processing (Laplante and Gray, 2005). Table 2-3 details the economic benefits that can be obtained when gravity concentration is implemented in an amenable circuit.

Table 2-3. The economic impact of (non-alluvial) gravity recovery (Laplante and Gray, 2005)

<u>Application type</u>	<u>Benefits</u>
Recovery of GRG ahead of cyanidation	Higher overall recovery
	Lower carbon costs
	Lower retention times in cyanidation
Recovery of GRG ahead of flotation	Higher overall recovery
	Better Net Smelter Return (NSR)
	Lower reagent costs
	Possible avoidance of cyanidation
Pre-concentration	Lower downstream processing and tailing disposal costs
Scavenging of GRG and gold carriers (cyanidation tails)	Higher overall recovery
	Coarser initial grind
Partial pre-concentration of gold carriers for intensive cyanidation	Higher overall recovery
	Coarser initial grind

Laplante and Gray (2005) have also demonstrated that overall recovery can improve when a gravity recovery circuit has been retrofitted in a plant. Although precise modelling of GRG particle size reductions in the grinding circuit is currently not possible feasible (Woodcock and Laplante, 1993), there exists an adequate understanding of grinding and hydrocyclone performance by which reasonable predictions of plant performance can be made when applying Laplante's GRG model.

2.5.3 Shortcomings of Gravity Concentration for Free Gold Recovery

A literature review highlights the importance of properties such as shape, porosity and natural hydrophobicity of gold on the recovery of GRG by gravity concentration (Burt, 1984; Koppalkar, 2009; Spiller, 1983). According to Laplante and Gray (2005) a gold particle's response to gravity recovery is highly impacted by aspect ratio or shape factor. Due to the malleable nature of gold, particles will

eventually, through comminution, assume a shape with a high aspect ratio, such as a platelet, flake or lamellae (Laplante and Gray, 2005). They suggest these shapes, combined with gold's natural hydrophobicity, can severely impact a particle's potential for gravity recovery. It has also been shown that flat gold particles which undergo further comminution will roll, forming cigar and eventually spherical shapes imbedded with gangue material (Banisi et al., 1991), as further discussed in 2.7.1.

Gravity concentration by BCCs is notoriously poor at recovering fine gold particles as well as gold in carriers (Koppalkar, 2009). Therefore, alternatives to gravity recovery should be considered when the GRG content is less than 25% of total gold, when the GRG is ultrafine ($-38\ \mu\text{m}$), or when the gangue material has a high specific gravity, making efficient separation difficult. Because of the variety of behaviours exhibited by gold in situ, it may be advantageous for an operation to employ several concentration and recovery methods to capture as much gold as early in processing as economically possible. The alternative processes include flash flotation leach feed pre-concentration, and using BCCS to scavenge coarse sulfides from leach tails. However, the use of gravity can be seen as a security issue, as well as a burden for sampling and metallurgical accounting (Koppalkar, 2009).

2.6 Flotation

The flotation process separates valuable minerals or metals from gangue material based on surface property differences, with an emphasis being placed on physical and chemical variables for gold recovery (Laplante, 2005). Conventional froth flotation, originally introduced in 1906, has allowed for processing of low grade and complex ore bodies which were previously uneconomical (Wills, 2006). Presently, conventional flotation is used in a variety of commodities from precious and base metals to coal and talc. In addition to mineral applications, flotation has also been used to de-ink paper in recycle processing. Flotation has become one of the most important and versatile mineral processing techniques, regardless of commodity and despite its relative complexity. Just as a resurgence in the application of gravity recovery has been driven by the innovation of new equipment, the introduction of

flash flotation has allowed for similar advances in flotation process design and plant operation.

In the beginning, flotation had limited applicability with a few locations in Canada, Australia and Korea using oil based frothers for flotation of complex and refractory ores (Dunne, 2005; Hoover, 1912). However, during the 1930s, the introduction of water soluble collectors, such as xanthates and dithiophosphates, allowed for differential flotation of sulfides which was a driving force in the inclusion of flotation in gold processing (Dunne, 2005; Taggart, 1945). Sulfide flotation concentrates were roasted and the off gases could be scrubbed to produce a sulfuric acid by-product, which was in demand in the uranium industry of South Africa (Dunne, 2005). In the following period and until the 1960s, Canada dominated gold flotation, enabling the country to become the world's second largest gold producer (Dunne, 2005). The increased demand for gold beginning in the 1980s led to continued exploitation of lower grade deposits and implementation of new extractive techniques such as bioleaching, pressure oxidation and, of particular interest to the current study, flash flotation.

2.6.1 Principles of Flotation

In its most basic description, flotation is the act of collecting a concentrate froth (or "con") from a vessel containing agitated slurry and a suite of reagents. Particles of interest selectively attach to the bubbles formed in the pulp by the induction of air and are carried to the pulp-froth interface. A generic cell diagram is given in Figure 2-8 to demonstrate the relative proportions of the phases present and locations of the streams involved in conventional flotation.

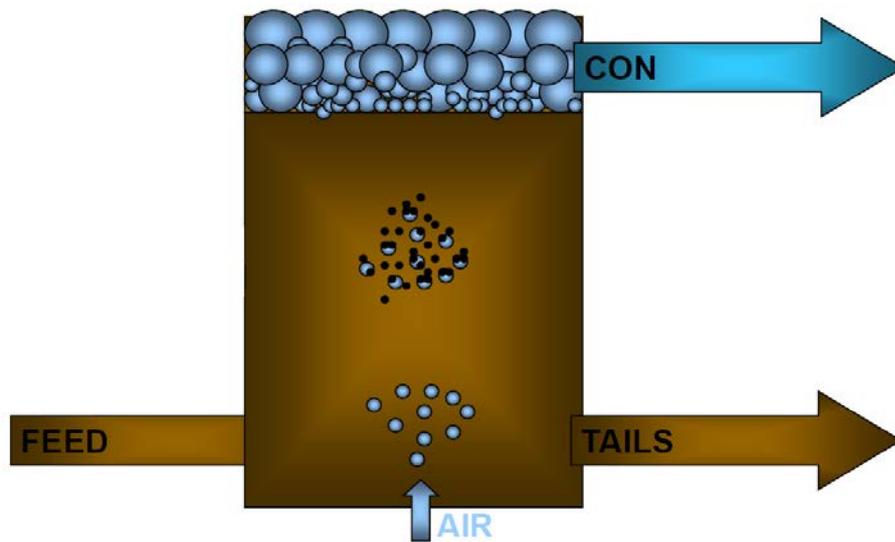


Figure 2-8. Basic froth flotation operation

The chemical, operational and mechanical factors enabling the separation and recovery of valuable material from gangue via the froth flotation process are reasonably complex. While these processes are all of great importance, only an overview will be presented in this review.

The chemical components affecting flotation performance mainly refer to the reagent suite, such as collectors, frothers, activators, depressants, and pH modifiers used in operation and testing. The chemical components are routinely evaluated in laboratory scale studies to identify opportunities for optimisation. Operational components can impact both laboratory and plant scale performance, and often there are problems with scaling up of these factors from laboratory to plant. They include:

- Feed rate,
- Mineralogy,
- Particle size,
- Pulp density, and
- Temperature.

Equipment components (for example cell design, agitation, air flow, and cell bank configuration/control) are primarily plant based factors which influence a flotation circuit. It is important to note that the three groups (chemical, operational and mechanical) of factors influencing a flotation system behave dynamically and are interconnected, making modelling and optimisation difficult, but possible.

Teague et al. (1999a) diagrammatically summarised the physical and chemical factors that are important for gold ore recovery, as can be seen in Figure 2-9. The figure outlines the impact of specific factors upon the behaviour of not only free gold but also gold sulfide ores. It is interesting to note that some factors (for example, the sequence of PAX and copper sulfate addition, temperature, pulp chemistry) can have the opposite effect on the recoveries of free gold and sulfides, further emphasising the difficulty in optimising parallel recovery of both mineral groups.

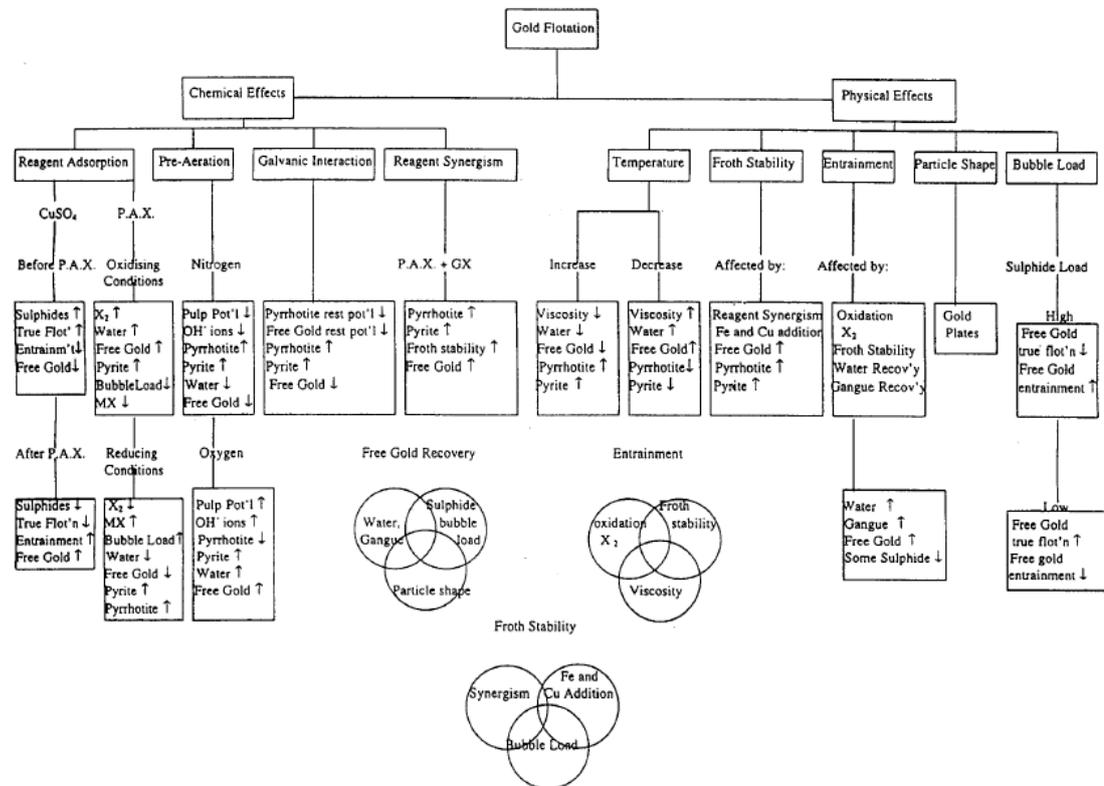


Figure 2-9. A conceptual model for gold flotation (Teague et al. 1999), permission granted by Elsevier

In the conceptual model for flotation offered by Teague et al. the possible effects of water, gangue, sulfide bubble load and particle shape are highlighted for impact on free gold recovery but the influence of other factors (such as surface coatings or the presence of clays) are not apparent.

2.6.2 Development of Flash Flotation

Lynch et al. (2010) suggest the history of flash flotation began with the first attempt at flotation of a ball mill discharge, made at North Broken Hill in 1933. In 1949, Cominco used Maxwell cells to scalp rod mill discharge with the resulting flotation concentrate cleaned in a Denver cell. The Davcra cell, tested in the 1960s, was the first high intensity flotation machine with a centrifugal feed stream and coarse tailings discharge, a precursor to today's flash flotation cell design. However, the Davcra machine was unconventional and, in general, not well accepted in the

minerals industry, except for in coal flotation. The SkimAir® flash flotation cell was developed by Outokumpu (now Outotec) in the early 1980s to “flash off” fast floating and liberated minerals of high value (Coleman, 2010). It was designed to be used ahead of conventional flotation in the grinding mill circulating load in order to reduce the over-grinding of sulfides (Bourke, 2002). The first mill to utilise the process was the Hammaslahti copper concentrator in Finland in 1982.

Flash flotation is often incorrectly referred to as coarse particle flotation though it is more simply about flotation of liberated, or mostly liberated, material from within the milling circuit, regardless of particle size. While flash flotation is similar to conventional flotation in terms of reagent schemes and flotation mechanisms, it does differ in the cell design, feed characteristics and operating strategy (MacKinnon, 2002). Newcombe et al. (2013a) have listed the key factors distinguishing flash flotation from conventional flotation as:

- Coarser feed material,
- Higher solids density in the feed slurry,
- Shorter residence time,
- Limited, if any, conditioning period, and,
- Lower power input by impeller to promote bypass of coarse material.

While the distinguishing factors listed are of significance it is also important to note the position within the circuit, water balance limitations and types of particles targeted for recovery. Flash flotation is positioned within the recirculating load of the milling circuit, and as such, it targets recovery of liberated, un-oxidised sulfides and fine free gold. In order to float these particles in the high solids density of the milling circuit stream, water additions must be carefully controlled to maintain balance within the circuit. One of the key differences between flash flotation and conventional flotation is residence time, of particular importance when evaluating recovery versus grade curves which usually indicate that a large proportion of the valuable mineral will float quickly while a smaller portion will float slowly or not at all. Modelling these trends with various kinetic rates is discussed further in Section

2.8. These factors, in conjunction with those previously listed, make design and operation of flash flotation units quite different from those found in conventional flotation circuits.

In contrast to conventional flotation, early attempts at flash flotation involved a cell using mill discharge (as opposed to cyclone overflow) for the feed stream. However the vessel designs were poor and the units performed more as rougher flotation circuit which produced a concentrate containing a large portion of fine material. Flash flotation, in the most popular design in use today, has effectively dual functions; the process acts as both a hydrocyclone and a rougher flotation cell. Although it differs from conventional flotation by operational set points as well as cell design, the fundamentals of flotation remain unchanged.

The major design differences between mechanical flash flotation cells, presented in Figure 2-10, and conventional flotation cells are the conical bottom and dual outlet of fine and coarse discharge for optimising mill efficiency and flash flotation performance (MacKinnon et al., 2003).

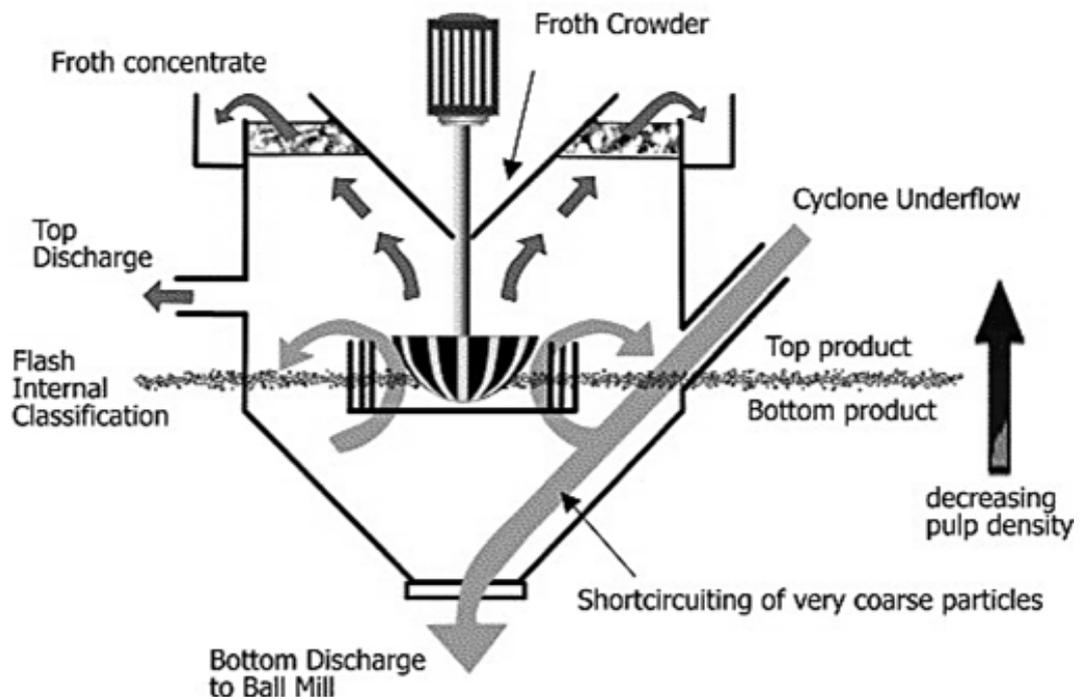


Figure 2-10. Flash flotation diagram (MacKinnon et al., 2003), permission granted by Elsevier

Upon entering the flash flotation cell coarse material is short circuited to the bottom discharge preventing interference with the flotation zone where it could lead to a higher pulp density than is desirable and prevent particles from rising to the surface (MacKinnon et al., 2003). A study by Newcombe et al. (2013a) demonstrated slurry profiles change with increasing depth showing trends of increasing slurry density, coarseness and segregation based on a particle's density. This supports the description of flash flotation by MacKinnon (2002). A low density fines stream allows for an optional side outlet which acts to deslime the feed material upon entry into the vessel. This adds to the increasing solids density profile with depth in the unit and helps to cope with different water requirements of the flash flotation and grinding circuits (MacKinnon et al., 2003). Not only does the process supply a more stable feed grade to downstream flotation cells by removing fluctuations in head grade, it can also improve overall recovery, mill throughput and plant dewatering (Outotec, 2009). It allows an opportunity for differential flotation in a low mass pull

device, where the target is to selectively recover certain particles by subjecting the slurry to different flotation conditions prior to a conventional flotation circuit.

As with conventional flotation, the effects of mineral properties, reagent type and dosage, residence time, cell characteristics and impeller speed must be considered, but it has been suggested that particle size, aeration rate and pulp density are the three key factors affecting the performance of a flash flotation unit (MacKinnon, 2002). Flash flotation has usually been included in the design stage of a plant, as opposed to retrofit and, because of this, limited opportunities have existed to measure the impact overall recoveries for a plant with and without flash flotation installed. A refurbishment in 2003 at the Leinster nickel plant in the Western Australia's Eastern Goldfields region required the concentrator to operate for a period without flash flotation which had been included in the process since the early 1990s. The change resulted in a size distribution shift containing an increased portion of fine ($\sim 7 \mu\text{m}$), slow floating material (Warder and McQuie, 2005). Newcombe et al. (2012a) examined the role of flash flotation in a gold concentrator and found the industrial units recover only fast floating, well liberated, $<150 \mu\text{m}$ material in a study focused on bulk sulfide recovery (the gold was of a solid solution refractory nature), further supporting the use of flotation for recovery of fine GRG and non-GRG material alike.

2.6.3 Flash Flotation of Free Gold

If there is fine free gold present in a milling circuit, flash flotation may be used in one of several configurations (with or without gravity concentration) to process the ore. Most commonly, flash flotation is used to treat a portion of the cyclone underflow in a closed loop milling circuit with the objective of recovery of gold carriers (sulfides) by limiting overgrinding. When no GRG is present, flash flotation can be used as a pre-concentration step for gold carriers (sulfides) in the grinding circuit which feed a subsequent oxidation processes. The objective, when targeting non-GRG material, is often to recover the sulfides in to a concentrate as a feed material for ultrafine grinding (UFG), roasting, bio-oxidation or pressure oxidation. If the host, pyrite or even more so, arsenopyrite or pyrrhotite, remains in

the recirculating load then subsequent oxidation of the particle surfaces may lead to poorer recovery in conventional flotation.

Flash flotation can be a viable processing option for free gold recovery when GRG is present at concentrations too low or particles sizes too fine to warrant a BCC, and when conventional flotation is already used downstream. When GRG content is significant, BCC and flash flotation can both be used for its recovery within the milling circuit (these relationships will be further discussed in Section 2.12). It has been suggested that fine gold particles are strongly hydrophobic and therefore are good candidates for flash flotation (Laplante and Dunne, 2002a). Teague et al. (1999a) have shown that flotation of free gold is affected by physical factors such as shape and size of particles, degree of water and gangue transport to froth, stability of the froth, and extent of sulfide bubble loading which provides a barrier to hydrophobic bubble attachment of free gold.

As previously indicated, the effect of full scale flash flotation on the recovery of free gold has been difficult to determine as flash flotation has been most often introduced at the design stage and there have been little plant data available for free gold recovery before and after the introduction of the process (MacKinnon et al., 2003). Recent work by Newcombe et al. (2013b) demonstrated there was an increase in the amount of sulfur (inferred as pyrite or arsenopyrite) reporting to the cyclone overflow (conventional flotation feed) as a consequence of taking a flash flotation unit off line during a survey. Newcombe et al. (2013b) determined this shift in cyclone overflow composition led to decreased overall recovery, with the flash flotation contributing around 42% of the gold reporting to final concentrate during normal operation at the survey site (Kanowna Belle, Western Australia) though no fundamental explanation for the reduced recovery is given. The importance of flash flotation could be determined if all the additional gold carrying sulfides were not recoverable due to surface oxidation, then the role of flash flotation to recover reactive sulfides before they are rendered unfloatable would be demonstrated for this case. Other than the exploratory work by Laplante and Dunne (2002a) there have

been no other published studies on the free gold recoveries by flash flotation at this time.

Currently, there are laboratory flotation tests available to predict the behaviour of ore in a sulfide flash flotation circuit. These procedures have been comprehensively researched by Newcombe et al. (2012a) and MacKinnon et al. (2003). Similar testwork programs are offered commercially by companies such as Outotec (2011), Gekko Systems (2011) and Minnovex Technologies (2011). Until now, Laplante's GRG test was the only method available which could estimate an expected recovery of free gold in a flash flotation cell. This indirect approach requires extrapolation of the GRG test to provide an estimate about the expected flash flotation recovery of GRG material, with no site specific flash flotation data used in the approximations.

2.7 Factors Affecting Free Gold Flotation Performance

There is a noted lack of fundamental work on the flotation of gold or gold minerals in refractory or copper ores due to their low concentrations, with what has been reported based on specific ores without distinguishing between free gold and other gold minerals or bulk sulfide floats in general (Dunne, 2005). An extensive literature review suggests nearly all information that does exist in the realm of free gold flotation is related to conventional flotation and requires additional research or extrapolation to be applied to the field of flash flotation.

Klimpel (1999) suggests the factors most influential upon the recovery of free gold in flotation are, in order of significance; size, collector type and dosage, and frother, while pulp density, lime, temperature and simultaneous flotation with sulfides are also suggested to play a role in floatability. Researchers have performed extensive studies on the floatability of gold particles and have found the major factors affecting free gold's flotation response to be the silver content in native gold and that collector loading is proportional to silver on the gold surface (Chryssoulis, 2001; Chryssoulis and McMullen, 2005; Chryssoulis et al., 2003). Chryssoulis et al. also demonstrated that large gold flakes require more collector addition, up to four

times more for tarnished, coarse gold as compared to smaller, shiny grains. This observation is then offered as an explanation for the tarnished gold flakes observed in the flotation tails of many plants. In addition they suggest that pyrite competes with gold for the collector potassium amyl xanthate and only after the pyrite is removed will PAX load onto the gold particles.

2.7.1 Physical (Particle Parameters)

The flotation of free or liberated gold is greatly impacted by physical constraints, such as size and shape of the particles, as well as froth stability and bubble loading (Dunne, 2005; Teague et al., 1999a). The physical factors having a possible effect on the recovery of free gold selected for discussion in this section are liberation, size, elemental composition, rimming, roughness, coatings, surface area, shape, milling effects, hydrophobicity, surface refreshment, bubble loading and kinetics.

Liberation

Liberation refers to separation of the valuable material from the gangue minerals within an ore. Historically, gold associated with sulfides (typically pyrite) would require comminution to $P_{50-80\%}$ 75 μm for liberation sufficient for flotation, unless the ore was very high grade or gold was at a premium, finer grinding was deemed uneconomical (Klimpel, 1999). When Newcombe et al. (2012a) explored the nature of an industrial flash flotation concentrate, they noticed it was comprised of well liberated material, less than 150 μm . The study, focused on bulk sulfide recovery, made no comments about the content or nature of free gold in the concentrate material.

Highly liberated particles allow for more surface area for interactions between the target mineral and the reagents used to float them, and will therefore float better (faster kinetics and greater overall recoveries) than similar sized particles containing a larger proportion of gangue. Review of the available literature suggests that satisfactory flotation of free gold can be achieved with little or no pH regulation

coupled with small collector and frother reagent dosages; it is likely this would hold true in the recovery of free gold in flash flotation since those conditions would be met.

Size

Particle size has a strong influence on recovery and flotation kinetics for multiple reasons. Firstly, liberation is directly related to particle size and flotation will only proceed when a particle is sufficiently liberated (Zheng et al., 2010). A chalcopyrite flotation study has shown that a coarse liberated particle floats similarly to an intermediate partially liberated particle, and a coarse unliberated particle will float slower than an intermediate particle of similar composition (Newcombe et al., 2012b; Sutherland, 1989).

Secondly, there is a size limit at which a particle is too large to float. Large particles, which are heavy (especially considering the density of gold), are prone to detachment from bubbles due to gravity and the forces of drag. In addition, bubbles attached to a coarse gold particle may not have the required buoyancy to transport the particle to the froth interface and suffer loss of valuable particle during collisions with other particles (MacKinnon, 2002). With gold, due to its malleable nature, a particle may be smeared and not actually be “large” in terms of mass but rather in terms of a two dimensional, flat shape. In general, recovery is maximised in the 10-100 μm size fraction and drops off significantly above and below that range, with few particles greater than 300 μm able to be floated (Trahar, 1981). In a laboratory setting, coarse particle flotation, in this case $+300 \mu\text{m}$, has been shown to consistently result in lower recoveries than the same ore in a plant flash flotation circuit, which is explained by better hydrodynamic conditions present in the full scale unit providing the conditions required for coarse and dense particle recoveries (MacKinnon et al., 2003). In most flotation plants, sulfide particles larger than 150 μm are considered too large for conventional flotation though it is a widely held misconception within industry that flash flotation can, and will, recover larger particles (Newcombe et al., 2012b).

Thirdly, research has demonstrated that reagent additions and pH control have a greater significance on coarse particle flotation behaviour and recoveries than for finer sizes (Trahar, 1981). For example, Lins and Adamian (1993) found that gold grains smaller than 160 μm were floated efficiently with just a frother while larger gold particles also require the use of collector. Trahar (1981) proposed that the increased surface area of a large particle requires more extensive collector coverage than a smaller particle to obtain the required degree of hydrophobicity and ensure bubble-particle attachment strength is sufficient to withstand disruptive forces.

Elemental Composition, Rimming, and Coatings

Often, free gold is contaminated or tarnished in the milling process. Chryssoulis and Dimov found gold particles with surface contamination (in this case, mercury thiochloride) tended to report to flotation tails while those with cleaner surfaces were more likely to report to the concentrate (Chryssoulis and Dimov, 2004; Chryssoulis et al., 2003). Chryssoulis and Dimov (2004) were able to show that leaching of surface contaminants led to increased recovery by flotation of fine gold in laboratory tests, and a related plant study. It has long been known that flotation recoveries are also diminished when free gold particles contain fine grained embedded gangue which decreases hydrophobicity (Taggart, 1945). Malhotra and Harris (1999) stated that iron tarnishing on free gold particles will prevent flotation, which was supported by research by Brook et al. (2003), in which iron rimming had been shown around gold core particles in gravity concentrated flotation tails samples.

Conversely, silver activates gold flotation and there is a strong correlation between the surface concentration of silver on gold reporting to concentrate streams and the degree loading of certain collectors (Chryssoulis and Dimov, 2004). This suggests particles found in concentrates will have higher silver to gold ratios than particles reporting to tails, all other factors being equal. Further discussion concerning preferential collector loading between silver and gold is presented in Section 2.7.2.

Shape, Roughness and Surface Area

Although it has long been speculated that angular or flat particles are easier to float than rounded particles, it is unclear as to which of the flotation subprocesses (collision rate, attachment efficiency, bubble-particle stability, entrainment, etc.) are specifically affected by the particle shape. Therefore, a particle's shape, roughness and surface area can potentially impact the floatability and possibility for recovery in a myriad of ways. It has been identified that these properties can affect the motion through the slurry, in terms of settling rate and drag. For example, in theory, spherical gold particles should settle quickly while in comparison, flat particles of similar composition and volume would stay suspended in solution longer due to increased drag in a still or slow moving fluid.

There have been few systematic studies on the effect of particle shape or roughness on flotation performance (Verrelli et al., 2014), specifically in the case of free gold. Particle roughness, or texture, has been estimated by generating shape descriptors from 2D scanning electron microscope (SEM) measurements via Fourier analysis (Ahmed, 2010; Bowman et al., 2001). Drawing from the principles describing the effect of particle roughness in fluid mechanics (Shockling et al., 2006), it is likely a particle's roughness will have little effect in the region of laminar flow as compared to a more pronounced effect expected in the turbulent flows of a flotation vessel pulp. In addition, the drag, type of wake and associated pressures expected would be different for spherical and elongated particles. Not only will dense gold particles rotate to the bottom of the bubble from the original point of attachment they will be more likely to disengage after attachment due to bubble particle interactions and, in the case of flat particles, a large contact angle (as suggested in Figure 2-11).

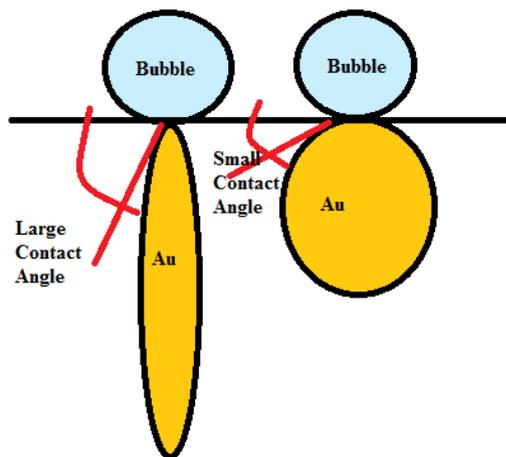


Figure 2-11. Proposed attachment and contact angle differences between flat and round gold particles

The mechanism for parallel presentation of a flat particle relative to the direction of pulp flow in turbulent flow has been demonstrated previously (Rhodes, 2008), and is incorporated in the proposed attachment of flat gold particles to bubbles as it is expected to minimise drag as the pair move through the slurry. Gold particles with pear, flake or needle shapes are expected to form a large contact angle with the bubble, increasing the possibility of detachment due to drag and eddies in the wake. Many other irregular shapes also fit this scenario, and in almost all cases increased likelihood of detachment would be expected as less force will be required to separate particles from bubbles with a large contact angle (Drzymala and Vigdergauz, 2000). In addition to shape, surface area and roughness play a role in bubble particle attachment (contact angle) and the force required to separate them (work of adhesion). The effort required in both cases will differ depending on particle geometry (Drzymala and Vigdergauz, 2000). This is particularly true in high density pulps typical of flash flotation (MacKinnon, 2002). Interestingly, laboratory testwork concerning the shape effect of glass ballotini particles on flotation recovery by Koh et al. (2009) demonstrated flat, elongated particles were recovered better by comparison, while roundness and relative width had a negative impact on flotation recovery. Their research suggests the rotation around the bubble and large contact angle may not be sufficient enough for detachment to occur in all cases.

Laboratory tests have found surface roughness to increase flotation kinetics in the case of quartz particles (Ahmed, 2010; Rahimi et al., 2012). In addition, it was shown that the influence of surface roughness had a greater impact than shape in kinetic studies of quartz flotation (Rahimi et al., 2012); however results reported in these studies may be mineral specific. Again, increased flotation response and kinetics were proportional to angularity for quartz particles in recent studies performed by Verrelli et al. (2014), which also demonstrate a marked decrease in the induction period (time available for particle to slide across a bubble surface and attach) for more angular particles. However, the authors were clear that malleable particles (such as gold) deform plastically during processing and are not expected to behave identically to brittle materials, like quartz. Gold will stretch, smear and shear off into smaller particles while brittle minerals are likely to fracture at stress points in the lattice caused by defects in the crystal structure, with the progeny maintaining similar shapes to the parent particles.

Askoy and Yarat (1989) proposed that native gold flakes have highly roughened, flat surfaces and that greater roughness is responsible for decreased bubble attachment and floatability. Allan and Woodcock (2001) claim the opposite is true; rather that flat particles present a larger surface area for collector and bubble attachment and settle more slowly offering greater floatability than cubic particles of similar composition. Results of a gravity recovery study confirm gold particles lost to BCC tailings are usually flatter than the concentrate particles, as a consequence of their inherent floatability and being carried away by the fluidising bed water (Koppalkar et al., 2011). This suggests that recovery by flotation or gravity in the intermediate size range may be heavily shape dependent.

The irregular shapes of free gold particles can be hard to measure consistently. Some researchers have used two dimensional shape determinations such as circularity, aspect ratio, compactness, elongation or the Corey shape factor (CFS) as a way to quantitatively assess the particle's flatness (Allan and Woodcock, 2001; Tourtelot and Riley, 1973; Wang and Poling, 1983). In this research the 2D circularity shape factor will be calculated from SEM images generated during

QEMSCAN analysis as well as 3D surface area to volume ratios from Micro CT. These factors are then used as a measure of circularity/sphericity, a method for determination of deviation from an ideal circle/sphere, and in describing and comparing gold particle shapes.

Milling Effects

The effect of milling will also have an impact on recovery in flotation as free gold particles do not fracture but rather smear and may become flaky due to malleability (Aksoy and Yarar, 1989; Brook et al., 2003). With continued comminution, free gold particles form a secondary shape by rolling into a cylinder or tube form, while others become a compact, spherical form displaying signs of breakage as proposed in Figure 2-12. In this case, these spherical milled particles yield decreased floatability (Banisi et al., 1991) due to gangue impregnation and surface coatings.

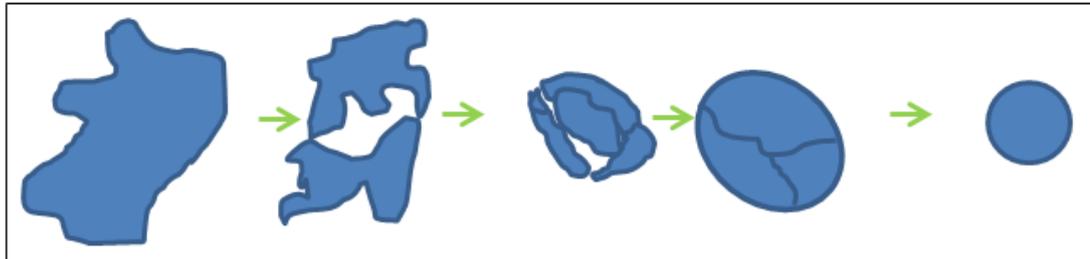


Figure 2-12. Proposed changes in free gold shape as a function of residence time in the milling circuit

Not only does the milling process change the shape of a particle, potentially leading to decrease flotation response, but milling is also known to impregnate free gold with gangue and other non-flatable materials (Taggart, 1945) which leads to decreased hydrophobicity. Pevzner et al. (1966) proposed the surface of gold may even be passivated during the hammering action of steel media balls in comminution, while Allan and Woodcock (2001) maintain the opposite is true, that is work hardening (plastic deformation of the surface of the metal) of the gold due to milling may actually increase the surface activity and affect the adsorption of reagents. If the

hypothesis of Allan and Woodcock is correct, than passivation, as suggested by Pevzner et al., may be due to surface chemistry effects such as iron oxide slime coating as a result of media wear as opposed to the impact of mill media.

Hydrophobicity

The subject of gold's inherent floatability or natural hydrophobicity is complex. Research by Tennyson (1980) demonstrated that pure metallic gold displays a contact angle of zero indicating the surface is naturally hydrophilic. The hydrophobic behaviour often displayed by gold particles is due to a high Hamaker constant (Drzymala, 1994). The approach of Hamaker assumes complete additivity of forces between individual atoms and is called the microscopic approach to van der Waals forces. A high Hamaker constant is indicative of Van der Waal's interactions resulting in a strong dispersive attraction for water (Dunne, 2005). Although the van der Waals interaction for gold is already well-understood, the calculation of the relevant interaction to the bubble-particle interaction in flotation remains a problem (Nguyen et al., 2001). Studies by Nguyen et al. (2001) have aimed to show how the van der Waals interaction energy can be calculated for mineral particles, which are assumed to be spheres, but for simplicity, the problem of the effect of the particle surface roughness on the van der Waals interactions was not addressed.

In a process referred to as collectorless flotation, fine free gold will float better than gangue material without the addition of collector and research has shown untarnished gold, of the appropriate size, can be readily floated with only a frother (O'Connor and Dunne, 1994). Similarly, Klimpel (1999) found that smaller gold particles will float faster and achieve higher ultimate recoveries than larger free gold particles in the presence or absence of a collector. The study also reported flotation plants achieved reasonable recovery of free gold particles <150 μm , regardless of collector use.

The floatability of gold is known to be enhanced by surface coatings of some organic compounds and high silver content (either as rimming or in the form of electrum), while calcium ions and some forms of sulfur can act as depressants.

However, when native gold surfaces are hydrophobic due to contamination by naturally occurring organics, the fine gold particles may be harder to recover by flotation (Aksoy and Yasar, 1989).

Surface Refreshment

Interestingly, free gold can be floated with low quality water (such as sea water) with little, if any, loss in recovery or decrease in grade because it is a naturally floating mineral, not very sensitive to many water chemistry factors (i.e. hardness, ionic strength) (Klimpel, 1999). A recent study by Guo et al. (2013) has demonstrated the deleterious effect of weak acid dissociable (WAD) cyanide on the flotation recoveries of gold and silver species. Other research has suggested chemical process coatings and small particle slime layers are the major contaminants on the surface of free gold which decrease hydrophobicity (Klimpel, 1999). Klimpel (1997) suggested liberated gold particles can be recovered selectively from pyrite by keeping the surfaces clean from organic contaminants and adhering slime particles while bench scale tests reported by Monte et al. (1997) have shown the ability to selectively recover gold from pyrite after addition of an oxidising agent (hydrogen peroxide) with PAX as a collector. It has been noted that tarnished gold particles appear in flotation tailings more often than in concentrates, when there are no other obvious factors evident for their inability to be recovered (Chryssoulis and Dimov, 2004; Chryssoulis et al., 2003). Laboratory researchers have often employed surface refreshment techniques to sulfide minerals to remove oxidation products, though no published studies could be found to demonstrate if the same techniques may be required to remove tarnish from free gold and improve floatability in laboratory flotation testwork.

Bubble Loading

Reduced recovery of free gold may be experienced when there is competition with sulfide minerals for bubble attachment sites (Dunne, 2005), referred to as bubble loading or crowding. Teague et al. (1999b) observed that free gold cannot attach well to bubbles loaded with sulfide particles and hypothesised it is because of

the incompatible shape and surface texture of free gold. It is also possible that the sulfide material present in the slurry decreases free gold recovery by competition for collector as well as changes made to the pulp chemistry of the slurry that decrease collector loading on to free gold.

2.7.2 Chemical (Reagent Additions)

In gold ore flotation, there are two groups, free gold and gold in carriers (sulfides), which are targeted differently in terms of overall gold recovery. Determining the correct operating conditions and optimal pulp chemistry for the target particles will lower reagent costs and yield improved recovery of the desired species (Klimpel and Isherwood, 1993). In industry, there is a greater emphasis on matching the associated gold mineralogy to an ideal reagent scheme (Klimpel, 1999), rather than in laboratory testing. This is because laboratory work is not directly scalable and flotation recoveries tend to be very site specific.

Collectors

In order to float, a mineral needs to exhibit hydrophobic characteristics. Most minerals require the addition of collectors to produce sufficient hydrophobicity for effective recovery by flotation. Collectors are usually organic surfactants which lower the interfacial surface tension between the liquid and the solid particles in the slurry. In conventional flotation they are added during a conditioning period to allow for adsorption (Wills, 2006). In flash flotation, collectors are added near the point of slurry entry into the cell leaving little, if any, conditioning time. The presence of a collector reduces the stability of the hydrated mineral surface and allows attachment of a gas bubble to the mineral surface (Wills, 2006). Ideally, the collectors are selective, attaching only to the surface of specifically targeted minerals, as summarised in Figure 2-13.

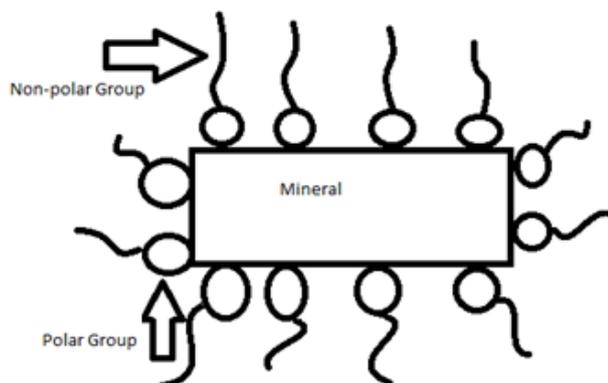


Figure 2-13. Collector chemisorption/physorption on the mineral surface

Collectors can be ionising, non-ionising, anionic, cationic, amphoteric, etc. These relationships are shown in Figure 2-14.

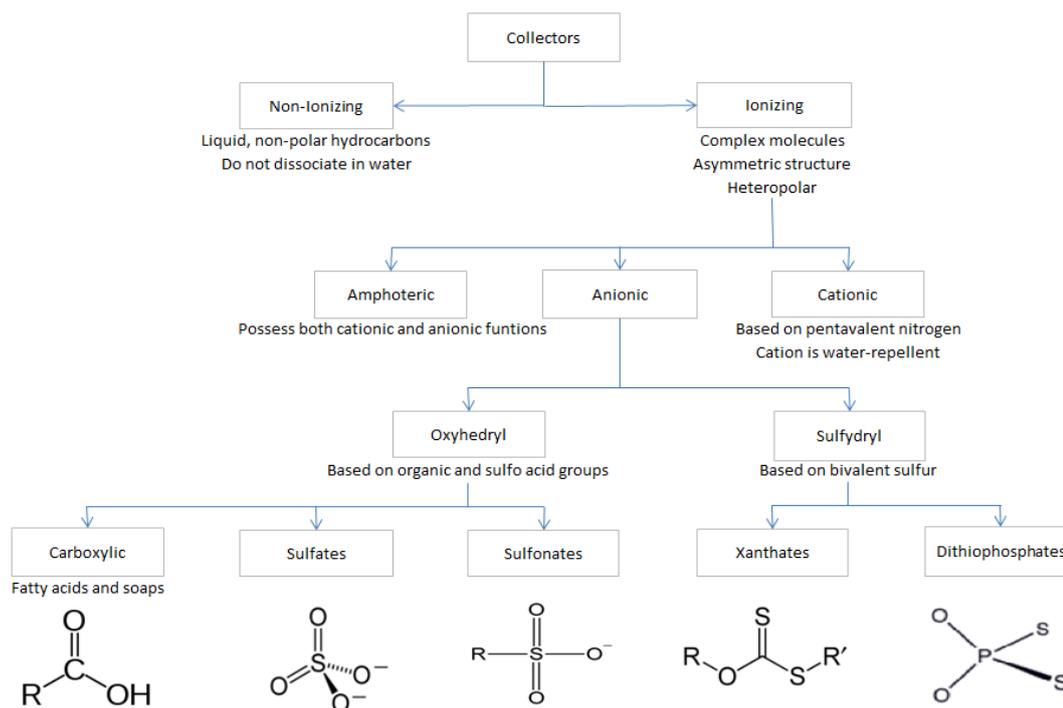


Figure 2-14. Classification of collectors (adapted from Wills, 2006)

Ionising or Non-Ionising

Insoluble collectors, or non-ionising collectors, create hydrophobicity by coating the surface of a particle. Collector molecules which dissociate into ions in water are called ionising collectors. These large, asymmetrical compounds are heteropolar and include a nonpolar hydrocarbon group. This results in a molecule that has both a water-repellent group and a polar group, which bond to the mineral surface. As shown in Figure 2-13, collectors adsorb with the non-polar ends orientated towards the slurry which creates hydrophobicity. Ionising collectors have a wide range of applications in flotation and are classified in accordance the type of ion producing the hydrophobic effect. It is common for several collectors to be added at various points in a flotation circuit to promote optimum recovery.

In order to obtain maximum selectivity and economic performance, ionising collectors are used in small doses, just sufficient to form a monomolecular layer on the particles of interest. In fact, over use of collector can have an adverse effect on recovery, possibly because multi layers formed on particles can reduce the proportion of nonpolar groups oriented towards the slurry. In addition, chain length and structure have an effect on solubility and adsorption. For example, branched carbon chains demonstrate a higher solubility than straight chains and carbon chains more than five atoms long exhibit diminished solubility, thus they are usually kept between two and five. Cationic collectors produce hydrophobicity by a pentavalent nitrogen group, most often an amine. Cationic collectors exhibit a relatively weak collecting power and, unlike xanthates, are considered to adsorb onto the mineral surface due to electrostatic forces. Amphoteric collectors possess a cationic or anionic function, depending on pH.

Anionic collectors are separated into two groups, the oxyhydril and sulfydril collectors. Oxyhydril collectors are organic acids or soaps (salts of fatty acids) displaying organic and sulfo-acid anions as the polar component. The organic acids, carboxylates, occur naturally in animal fats and plant oils and are strongly hydrophobic, showing little selectivity and are used to float alkali and alkaline earth metals and nonferrous metals. The sulfo-acids display a lower collecting power and

as such are more selective. They display similar properties to the fatty acids and are used to float barite, apatite, mica and cassiterite.

However, the most widely used collectors are the sulfhydryl type where the polar group contains bivalent sulfur, or thio compounds. These collectors are powerful and selective in the flotation of sulfides. The mercaptans (thiols) are the simplest of the thio compounds. One group of thiols, called xanthates, are generally regarded as the most important collectors for sulfides, and often for free gold flotation. Xanthates are assumed to adsorb onto the mineral surface resulting in insoluble, hydrophobic, metal xanthates. Several studies have demonstrated that dixanthogen is the xanthate species responsible for gold flotation (Woods et al., 1994; Woods et al., 1995). According to Chryssoulis et al. (2003) the oxidation of xanthate ions to dixanthogen, shown in the following sequence of equations (Equations 4 and 5), occurs at the surface of gold particles to form a neutral dimer dixanthogen, X_2 .



The dixanthogen acts as an oily coating on the surface of the gold particles and renders them hydrophobic. The conductive surface of gold facilitates the transfer of electrons which acts to sustain the redox equations and catalyse the oxidation of xanthate in the bulk solution (Fuerstenau, 1984). Unfortunately, these redox reactions offer no selectivity of gold flotation over pyrite.

Dithiophosphates comprise another subgroup of thiols. They are comparatively weak collectors compared to xanthates but offer good results when used in combination. Both types of thiol collectors require oxygen or another oxidising agent for flotation.

As previously mentioned, gold hydrophobicity is enhanced by the addition of collectors such as xanthates, dithiophosphates and dithiophosphinates, and untarnished gold requires less collector addition than tarnished gold to become

suitably hydrophobic (Chryssoulis and Dimov, 2004). Although xanthates have long been used in flotation plants to enhance gold recoveries because of higher recoveries and better concentrate grades (Dunne, 2005; O'Connor and Dunne, 1994; Wills, 2006), more recently the use of secondary collectors, or promoters, has demonstrated enhanced recovery, with dithiophosphates being the most widely used promoters in gold flotation (O'Connor and Dunne, 1994).

Free gold floats well in the presence of xanthate collectors but not if the particle size is too large, or if CaO or Na₂S are present (Teague et al., 1999a). As with tarnished particles, higher collector additions may be required to float coarser particles. Increased collector addition tends to accelerate kinetics and escalate ultimate recoveries, with the greatest impact noted on coarse particles (Klimpel, 1999). This concept is supported by the findings of other researchers, such as Gontijo et al. (2007) and Trahar and Warren (1976) which also demonstrated higher collector levels were required to float coarser particles. However, in studies performed on quartz, additional collector added with the intent to float coarse or tarnished material may instead have been consumed by fine particles with large surface areas per unit mass (Vieira and Peres, 2007). Flash flotation feed from the cyclone underflow, as often is the case, contains a decreased amount of fines, which are known to consume collector due to their higher surface area, therefore the collector added will be available to target more coarse material (Newcombe et al., 2012b; Vieira and Peres, 2007).

Understanding the size by effect that collector has on the recovery of the FRFG content of an ore is a primary objective in this research. PAX was the collector chosen for this testwork because it is readily available and often used in both laboratory and industrial flotation, so comparisons may be made between these results and data produced by other studies.

Frothers

Frothers are usually heteropolar organic reagents, chemically similar to ionic collectors. They form an organic layer around the bubble which increases bubble

stability and attaches to the non-polar ends of the collector, as illustrated in Figure 2-15.

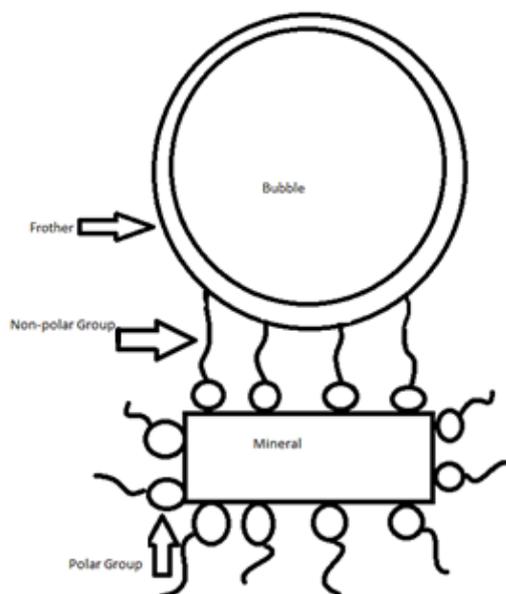


Figure 2-15. The interaction and attraction between bubble, frother, collector and mineral

While some collectors may exhibit frothing capabilities, the ideal frother should not provide any additional collecting power; rather it should act to optimise flotation kinetics by stabilisation of bubbles formed in the pulp and selective drainage of entrained particles from froth prior to discharge into the launder. A good frother produces a froth which is just stable enough to facilitate transfer of the collected particle from the flotation cell to the launder. The frothing action is facilitated by the ability of the frother to reduce surface tension and stabilise air bubbles via adsorption at the air-water interface.

Frothers are usually water soluble, as insoluble compounds will not disperse evenly through the slurry. Acids, amines and alcohols are the most widely used of the soluble frothers, with alcohols the most common due to their lack of collector properties. Historically, natural frothers such as pine oil and cresol have been used, but recently the use of synthetic frothers has increased. Improvements in control and

performance of the flotation process have been attributed to the replacement of natural frothers by synthetic versions, though cost, shelf life and availability have played an additional role.

Just as with collectors, individual sites choose frothing reagents based on mineralogy and process requirements, with some applications benefiting from a customised mix of frothers designed to provide ideal performance. Klimpel and Isherwood (1991) noted overall recovery of copper sulfide ores improved with increased reagent dosage in trials with an alcohol based frother. They explained that longer polyglycol chains lead to increased coarse particle recoveries while branching carbon chains lead to reduced recoverable particle size ranges. While many gold plants appear to prefer polyglycol ether-based frothers, used in combinations with other frothers, as noted by O'Connor and Dunne (1994) and Newcombe et al. (2013a), it is common for copper-gold ores (Dunne, 2005) and general laboratory testwork to utilise a weaker frother. One such frother, methyl isobutyl carbinol (MIBC), is often chosen for laboratory testwork because it is widely used and an easily available synthetic frother suitable for free gold and sulfide flotation.

Regulators

Regulators, or modifiers, are used to increase the selectivity of collectors by increasing or decreasing its hydrophobic effect on mineral particles. In this regard, regulators are further classed as activators, depressants or pH modifiers.

Activators

Activators promote hydrophobicity by means of alteration of the mineral surface by ions of soluble salts. Although flotation can be improved by the addition of greater quantities of long chain xanthates, often a more satisfactory and selective result can be obtain with the use of an appropriate activator. This is the case for copper sulfate use in differential lead-zinc flotation, and, to some extent, the flotation of galena, pyrite and calcite. Copper sulfate is widely used as an activator in sulfide (and to some extent, anecdotally for free gold flotation), as demonstrated at several plants (Dunne, 2005; Klimpel, 1999; O'Connor and Dunne, 1994). Teague et al.

(1999a) recommended that copper sulfate should be added after PAX in the circuit to promote free gold recovery. However, because the order of addition is specific, sulfide flotation is encouraged when copper sulfate is added prior to the PAX dosage. Yet, others claim to have entirely disproven the notion of copper sulfate activation of free gold. One explanation is that increased recovery by copper sulfate may actually be due to the activation of iron, which, in turn, is floated as iron-gold complexes created during grinding in the mill. This hypothesis seems to be supported by the fact that copper is less noble than gold and so it would not be expected to directly activate gold but rather iron (Monte et al., 2002). Though a proven mechanism for activation of free gold by copper has yet to be established (Dunne, 2005) it is plausible that the use of copper sulfate increases froth stability which contributes to the enhanced recovery of free gold with copper sulfate additions.

Activators are rarely required to float clean free gold (Woodcock et al., 2007). In analysis of testwork performed by Chryssoulis et al. (2003), silver was determined to be the only element which activated free gold flotation while chloride acted as the single most important depressant, which is important to consider in areas of highly saline process water, like Western Australia. The importance of silver in gold flotation has also been emphasised by Allan and Woodcock (2001) who found that pure gold (which is rarely, if ever, found in nature) is easier to render hydrophobic with the addition of silver. The silver content and distribution in free gold particles is examined in this research to determine its impact upon FRFG recovery.

Depressants

Depressants are used to increase the selectivity of a collector by making certain minerals hydrophilic which decreases their likelihood of floating. One example is the use of sodium silicate to deslime slurry (remove particles of less than 20 μm in size) by imparting a double layer charge on particles allowing dispersion. The clean mineral surfaces are then free to react with the available reagents without the interference of the slime layer. In this case, sodium silicate acts to depress the slimes and increases the target mineral's flotation response.

Depressants can either be inorganic or polymeric in composition. Inorganic depressants can be hazardous, for example cyanide when it is used in copper-zinc ore flotation, or sodium sulfide for depression of copper when floating molybdenum minerals. Due to the toxicity of some inorganic reagents, the use of organic compounds and polymers to depress minerals in flotation has increased. Reagents such as cellulose, dextrin and carboxymethyl cellulose (CMC) are now being used in platinum and base metal flotation. The Kanowna Belle mine site in Western Australia uses guar gum, a long chained organic polymer to depress sericite, an naturally floating mica mineral (MacKinnon, 2002). Interestingly, Marsden and House (2006) report that copper sulfate, which activates pyrite, has also been shown to depress gangue.

There are conflicting reports on the impact of depressants in literature (Aksoy and Yarar, 1989), and the flotation of native gold particles often proceeds sufficiently enough to not have warranted further investigations. However, some depressants for free gold flotation have been identified. These include, but are not limited to calcium ions, chloride ions, calcium carbonate, cyanide, sodium silicate, sodium sulfite, ferric and heavy metal ions, tannins and related compounds, starch and other organic depressants (Dunne, 2005). In some cases, these constituents are introduced inadvertently during the comminution and flotation processes.

At a gold processing operation the main concerns for the depressive action upon the floatability of free gold are usually calcium oxide (CaO), sodium cyanide (NaCN) and other WAD cyanide species. Lins and Adamian (1993) found that the addition of NaCN (up to 200 g/t) and CaO (up to 2000 g/t) do not act to depress free gold flotation when used with amyl xanthate as collectors; however gold depression was verified with an ethyl xanthate collector. Chryssoulis et al. (2003) identified the chloride ion as having the single most significant depression effect upon the floatability of free gold (gold bearing sulfides could be expected to have a different response), with the presence of iron oxides also contributing to a substantial depletion in recovery. Teague et al. (1999b) observed a reduction in the rest potential

of gold and a subsequent reduction in the activation and flotation response due to an interaction with metallic iron.

pH Modifiers

Industrially, most sulfide gold ore flotation plants do not regulate pH, as the unaltered pH of the slurry is generally sufficient for reasonable recoveries (MacKinnon, 2002). In the case of make-up water, pH adjustments may need to be made to the process water from tailings dams. Some gold mineral flotation is performed in basic pH conditions. This is because alkaline conditions promote stability of most reagents and minimise chemical corrosion of the piping and equipment and may be required as part of a downstream process, such as cyanidation. Adjustments to increase pH are usually made by the addition of lime and soda ash (sodium carbonate); less often sodium hydroxide and ammonia may be used. However, Healy (1984) recommends operating at as low as possible pH, avoiding rapid changes in pH, adding activator slowly or conditioning separately to minimise the impact of depressant formations at critical pH values. When pH is too high, additions of sulfuric or sulfurous acids are usually made to regulate the system.

Dispersants

Slime layers, such as those formed by talcs, clays, iron oxides and carbonates, which adversely affect the flotation of gold particles, can be controlled by the addition of a dispersant, for example, sodium silicate (Klimpel, 1999; Leaver and Woolf, 1934; O'Connor and Dunne, 1994). The use of dispersants must be thoroughly tested to determine any unintended impact upon the other chemicals used in the flotation system, though complementary reagent suites can be found to increase kinetics and overall gold recovery (Marsden and House, 2006).

2.7.3 Operational (and Mechanical Conditions)

Most of the operational and mechanical conditions discussed are intimately associated with each other. For example, bubble size distribution is tied to both the rotor/stator system as well as aeration rate (Newcombe et al., 2013a) and secondarily

controlled by chemical factors attributed to bubble coalescence and break up. These factors are interactive and, most times, hard to distinguish as independent variables.

Feed Type

The feed to a flash flotation unit is typically the cyclone underflow but may also be the mill discharge, whereas the feed for conventional flotation is usually the finer, more dilute product of the cyclone overflow. Cyclone underflow is a dense and coarse stream, at about 60-80% solids with rock and sand particles being common. Using the cyclone underflow as feed is usually a good choice because it provides a more concentrated amount of GRG material (Banisi et al., 1991; Laplante and Dunne, 2002a). Flash flotation feed is usually not conditioned, nor are reagent additions made at the higher dosages common to conventional flotation schemes. The top size for particles in industrial settings will vary, but laboratories generally use the minus 600 μm portion of the feed stream for testwork (Minnovex Technologies, 2011; Outotec, 2011; Systems, 2011). It is important to emphasise that despite the coarser feed stream, it is still the liberated particles that are being targeted by flash flotation which tend to be finer. The coarser free gold particles will be targeted by BCCs while there is a greater probability that the fine gold and gold carrying sulfides will report to flash flotation.

Pulp Density

Given the high solids density of the cyclone underflow feed stream, it is expected that flash flotation would operate at a higher density in comparison to conventional roughers in similar ore flotation circuits, which is generally 30-45 % (Nelson et al., 2002). Because flash flotation units are usually fed with a high solids density stream, the very coarse particles tend to short circuit the flotation zone and create a density profile within the vessel yielding a lower pulp density in the upper region where flotation is occurring. Not only does slurry density have an influence upon bulk recovery but it has also been shown to affect gas dispersion throughout the cell and result in larger bubble sizes (Newcombe et al., 2013a; O'Connor et al., 1990). High solids loading can also contribute to “boiling”, where dense slurries

prevent the dispersion of gas from the point of induction within the cell (MacKinnon, 2002). The dilution water added to flash flotation units decreases the solids density which is preferable for flotation but creates a challenge to maintain the water balance of the milling circuit. Most flash flotation units have the option for a fine tail discharge, which is a very dilute (<10% solids) stream that can be used to help maintain the water balance.

Conflicting reports of optimal pulp density for gold particle flotation have been given in the literature. Early mentions of the significance of pulp density by Leaver and Woolf (1934) suggest high pulp density for free gold flotation while Fahrenwald et al. (1936) suggested the opposite is true. More recently, Klimpel (1999) commented that a high pulp density of >30% solids, by weight, must be maintained in order to keep coarse free gold in the froth phase though Lins and Adamian (1993) recommend a low density pulp for flotation of free gold. MacKinnon (2002) proposed that high solids in the slurry will increase flotation kinetics due to a greater likelihood of bubble-particle collisions, although the increased frequency of detachment due to collisions with stray particles was also mentioned as an adverse effect.

Cell Hydrodynamics

Although hydrodynamic conditions are unique to each cell design, other factors, such as pulp density and aeration rates, will also affect the movement of the slurry. Residence time distribution survey data demonstrated that up to 31 % of a flash flotation cell volume is either short circuited, stagnant or recycling (Newcombe et al., 2012c) due to the vessel's coarse particle bypass design. In both fine and coarse particle flotation, the cell hydrodynamics have significant influence of upon recovery of a particle. While some authors suggest sufficient levels of turbulence within a cell required for recovering heavy particles is achieved at low agitation rates (Kallioinen and Heiskanen, 1993), others suggest high agitation rates are necessary to avoid sedimentation (Trahar and Warren, 1976). Hydrodynamic conditions within a cell are closely related to and mutually affected by slurry density, agitation and air addition rates, as well as vessel, rotor and stator design.

Rotor and Stator Type

Not only are the rotor and stator mechanisms responsible for agitation of the slurry (prevent sanding) and they also act as the point of entry for gas into the pulp. As such, they have a large influence on bubble size, which is a significant factor if the attempt is to recover heavy (coarse or dense) particles in a high solids density slurry. Most researchers agree that large bubbles, or agglomerates of smaller bubbles, are necessary to achieve the required buoyant force to lift heavy particles in a slurry and are therefore necessary in dense/coarse particle recovery by flotation. Individual plants make operation modifications, such as reduced impeller speed, targeting optimal bubble size and particle suspension in flash flotation (Newcombe et al., 2012b) to achieve preferential recovery of coarse particles compared to fine and intermediate particles of similar composition. However, it is important to remember the general target of flash flotation is usually to quickly remove liberated particles (not specifically coarse particles), regardless of size, in order to prevent overgrinding, sliming and oxidation. Lower impeller speeds may actually be targeted on site because as long as they suffice to keep the solids suspended the lower impeller speeds may actually reduce turbulence at the pulp/froth interface which promotes coarse particle recovery.

Vessel Design

Of the flash flotation circuits investigated in this research, the most common design of flash flotation tank is the mechanically agitated dual outlet and conical bottom design of the SkimAir® cell manufactured by Outotec. This type of vessel design varies from conventional units as it is specific to the nature of the feed material and its placement within the milling circuit. Maintaining the water balance is very important to the milling circuit and the dual outlet design in use by Outotec addresses this issue. More insight into Outotec vessel design and development can be found in Section 2.6.2 of this thesis, and in *The History of Froth Flotation* (Gorain et al., 2007). Occasionally, some sites will use column cells, or contact cells, for rougher flotation within the milling circuit. Column cells typically produce a higher

grade concentrate than mechanically agitated cells but the losses of coarse gold may be higher (Dunne, 2005).

Aeration Rate

The addition of air to a cell, or aeration rate, affects the gas hold-up within a cell, and is well recognised as a major factor in good flotation performance. Within the slurry, high aeration rates ensure there are enough bubbles available for particle collision, attachment and eventually recovery. Additionally, the aeration rate combined with frother will contribute to the depth and stability of the froth layer. As such, many plants regulate the froth level by a combination of reagent addition and air flow control (MacKinnon, 2002).

While both Ross (1990) and Kallioinen and Heiskanen (1993) agree that increased air flow is required to recover heavy particles, the latter also note recovery of both valuable and gangue material will increase, proportionally, with increased aeration rates, to an optimal point, after which, recovery will decrease with additional airflow. MacKinnon (2002) offers two hypotheses to explain this trend. Firstly, it is possible that excess airflow creates a pocket of air around the rotor where slurry is not agitated sufficiently; this has been referred to as “boiling” (Outotec, 2011). Secondly, over saturation of air into the slurry may cause coalescing of fine, well dispersed bubbles into larger, less stable bubbles. In either case, or in a combination of the two, it is best to target the optimal aeration rate which is very dependent on the design of the vessel and the rotor/stator mechanism.

Agitation

The hydrodynamic effects caused by agitation vary between plant and laboratory scale tests. Researchers at the Julius Kruttschnitt Mineral Research Centre (JKMRC) found that increased impeller speed reduced bubble sizes in laboratory vessels (5 L) while no effect on bubble size was measured in larger vessels (60 L) (Amini et al., 2013). The explanation offered for the different impacts of impeller speed was that smaller vessels have below critical turbulent kinetic energy (TKE) while the larger vessels were above critical TKE. The difference in TKE, or localised

velocity within the cell, offers an explanation for one of the reasons why plant scale work is so hard to scale up in flotation and how higher recoveries are possible in the plant compared to laboratory scale results. While the literature offers no specific recommendations for aeration rate for gold recovery, it is a factor that must be considered in combination with other operational set points when attempting to determine optimal flotation conditions.

Gas Mix

Oxygen is required for the flotation of sulfide minerals with thiol collectors, such as xanthates and this is also the case for free gold flotation. As discussed in the section regarding collectors, the surface of the sulfide mineral or gold particle is rendered hydrophobic by the chemical oxidation of the adsorbed xanthate to dixanthogen. Some conventional flotation circuits use gas mixes other than standard ambient air to achieve the desired flotation response. Although oxygen is generally believed necessary for gold and sulfide flotation with xanthate collectors, a study at the Lone Tree Mine suggested otherwise. Simmons et al. (1993) found better recovery of both gold and pyrite from an easily oxidised ore when floated with nitrogen instead of air, utilising the N₂TEC system.

In a study by Hintikka and Leppinen (1995) to assess the effects of potential control in a variety of slurries, a mix of flotation gases (air, nitrogen, etc.) was created to determine optimum conditions for recovery of target species. It was found that the optimal potential for gold flotation was between +250 and +300 mV vs. SHE, with decreases noted for increased silver content, in a system using ethyl xanthate collector. In cases of excess oxidation, reducing agents, such as sodium sulfide, can be added to restore the pulp potential to target levels (Dunne, 2005).

Slurry pH/E_h

In flotation, the main chemical effects are due to reagent addition and slurry pH (Dunne, 2005; O'Connor and Dunne, 1994), particularly for sulfides. Due to the costs of reagents and their impact on downstream processes, there is always a drive to operate at moderate pH with minimal reagent addition. E_h, refers to the

electrochemical potential relative to a hydrogen half-cell reaction and is a measurement of a pulp's oxidising/reducing power. While E_h has been shown to be a significant parameter in the flotation of precious metals and sulfide minerals (Hintikka and Leppinen, 1995; Jones and Woodcock, 1984; Woods, 1984), there has been less importance placed on E_h in pure gold flotation.

Highly selective reagents can help achieve and maintain the optimal pulp chemistry for a given ore, but unintended consequences may also arise. For example, when used in conjunction with xanthates, excess alkali reagents may depress sulfide species, resulting in a pH value termed the critical pH, where below that point, sulfides will float and above it, they are depressed. Lime (calcium hydroxide) is of specific concern as it is commonly used at many plants for pH control but may also act to depress pyrite and arsenopyrite when used with xanthates. In addition, excess lime has been shown to hinder the flotation of free gold by forming surface coatings of calcium and hydroxyl ions on the metal's surface (Chryssoulis, 2001; Klimpel, 1999).

It has been shown that naturally occurring free gold is best recovered in neutral pH, with the addition of a small amount of collector (Dunne, 2005). More specifically, (Klimpel, 1999) suggests the best recovery of inherently hydrophobic particles (such as free gold) is achieved by uncharged, water insoluble collectors, such as thiocarbamates, xanthogen formates, mercaptans and dialkyl sulfides, at the natural pH of the slurry. Hintikka and Leppinen (1995) found the optimum E_h range for native gold flotation in laboratory tests to be between +10 and +60 mV (vs. saturated calomel electrode or SCE). Extensive work by Woods et al. (1992), suggests chemisorption of xanthate on silver occurs over a large range of E_h -pH values. This is fortunate because gold plants often have less freedom over the control of water quality (specifically pH in this case) when the operation requires the use of recycled tailings water.

This is important because gold is rarely found in pure form naturally, but rather containing varying degrees of silver. Woods et al. (1994) found the silver sites in a native gold matrix are the first to adsorb dixanthogen and promote the flotation

response, showing increased floatability of free gold with increasing silver content. Therefore, the broad range of E_h -pH values favouring silver flotation with xanthates is expected to also indicate optimal similar conditions for flotation of gold and, even more so, naturally occurring silver-gold alloys (Allan and Woodcock, 2001; Woods et al., 1994).

Conditioning

The order and rate of reagent addition is of great significance in flotation of gold bearing ores (O'Connor and Dunne, 1994). Farrokhpay (2011) found increased conditioning with frother led to decreased maximum froth height as a consequence of increase in hydrophobicity for the particles. Generally, there is little or no conditioning time for the reagent addition to flash flotation circuits. This strategy is employed to encourage recovery of only the liberated, fast floating material. Woods et al. (1995) performed FTIR analysis to determine the effect of conditioning time on free gold and reported a decrease in the amount of chemisorbed xanthate on the surface of gold particles as a function of increased conditioning time. However, no additional testwork was performed to confirm whether this was only the case during analysis or if there is an effect of long term conditioning on collector coverage, flotation kinetics or overall recovery of gold.

2.8 Flotation Kinetics

The term kinetics is used to describe the rate at which a reaction, action or motion will occur. Flotation kinetics, the rate at which a particle is recovered to the concentrate, are determined by a mix of chemical, physical and operational/mechanical factors. Factor such as size, slimes present, collector levels, surface coatings and cold process water can decrease kinetics or result in poor collector adsorption to the metal and lower ultimate recoveries (Klimpel, 1999). Klimpel (1999) suggests naturally floating minerals will float rapidly, though it was also noted by Klimpel (1997) that gold will float slower than sulfide minerals as it is an intrinsically slower process than sulfide mineral flotation. Understanding the difference in kinetic coefficients between the target material and gangue in various

size fractions can allow for manipulations to be made which influence the concentrate grade. This is especially important in flash flotation where only the fast floating material can be recovered in the inherently short residence time of pulp in the cell. The kinetic models used to evaluate flotation rates in this testwork are discussed in Section 3.3.1.

2.9 Advantages of Flash Flotation for Free Gold Recovery

2.9.1 Selectivity and Grade

Kallioinen and Niitti (1985) published a study which reported the flotation kinetics of valuable materials and gangue could be exploited to optimise selectivity within given size fractions. As shown in Table 2-4, their work demonstrated that the selectivity index is not maximised in the same size fraction as the highest flotation rates are achieved.

Table 2-4. Flotation rate coefficients and selectivity indices for chalcopyrite and gangue material (Kallioinen and Niitti, 1985)

Size Interval (μm)	Flotation Rate Coefficients (min^{-1})		Selectivity Index S.I.= $k_{\text{chalcopyrite}}/k_{\text{gangue}}$
	$k_{\text{chalcopyrite}}$	k_{gangue}	
+149	11.78×10^{-3}	1.66×10^{-4}	71
-149 +74	17.70×10^{-3}	1.24×10^{-4}	142.4
-74 +37	40.73×10^{-3}	2.91×10^{-4}	140
-37	36.44×10^{-3}	9.24×10^{-4}	39.5

Ultimately, the results reveal that entrainment (mechanical carry-over of valuable particles into the concentrate) is more significant in the finest fraction which coincidentally marks the expected lower limit of competition between flash flotation and BCC recovery. Selectivity is best in the -149 +37 μm size range due to the non-selective nature of gangue flotation. Unfortunately, the information and trends presented must be tested for free gold ores, especially as the mechanisms for free

gold flotation are dissimilar and gold is known to display slower kinetic coefficients than similar sized sulfide minerals. However, the implication exists that free gold concentrates could be optimised for selectivity and grade if plants had site data to generate selectivity indices for individual ores.

Knowing that entrainment is greater for fine particles (Feng and Aldrich, 1999), it is expected there would be fewer fine particles in flash flotation systems due to the nature of the feed (cyclone underflow) and with the top outlet aimed at removal of fines via centrifugal forces within the vessel. Therefore, the design of flash flotation cells helps contribute to higher grade concentrates by rejection of fine gangue particles. Some mills which are not able to achieve the desired grade or mass pull from their circuits, operate the flash flotation as a rougher with cleaner cells and sometimes a regrind circuit to upgrade further which yields a high grade sulfide concentrate due to the selectivity and rapid kinetics of sulfides (MacKinnon, 2002). There currently exists no published information about the kinetic behaviour of free gold in flash flotation conditions.

2.9.2 Improved Recovery

According to Plouf and Malhotra (1989), one of the highlights of flash flotation is the improved recovery offered by minimising the overgrinding of polymetallics within the ore. Various sites have reported a decrease in overgrinding and tailings loss as a result of retrofitting a flash flotation unit into the milling circuit (MacKinnon, 2002; Warder and McQuie, 2005). Though there has been speculation as to the actual contribution of flash flotation to overall recovery, a plant survey performed at Kanowna Belle in Western Australia has validated the use of flash flotation to improve sulfide recovery for refractory ores. The survey monitored overall sulfide recovery with and without flash flotation. There was a measurable decrease in the overall recoveries of both gold and sulfide minerals during the period when the flash flotation circuit was taken off line (Newcombe et al., 2013b). This suggests that flash flotation plays an important role in early removal of gold and gold carrying particles which would be subsequently rendered unrecoverable in

conventional flotation (possibly due to surface coatings, gangue impregnation, changes in shape or oxidation).

2.9.3 Reduction of Overgrinding/Power Consumption

The prevention of overgrinding valuable minerals and unintended production of fines is an objective for all mills. The concern is not limited to just sulfide ores but is also extended to free gold because the fine gold particles will tend to report to cyclone underflow due to their high specific gravity in comparison to gangue minerals. Chryssoulis and McMullen (2005) claim that free gold grain losses to the slimes (less than 5 μm) are the main cause of free gold rejection in flotation plants. Not only do the fine particles require energy (and money) to produce but they are potentially lost in tailings streams as they are notoriously hard to float (Mulleneers et al., 2002; Trahar and Warren, 1976). Chryssoulis and McMullen (2005) further suggest that efficient performance of flash flotation is likely explained by flotation at an early stage of liberation, not only limiting the overgrinding of gold grains, but also reducing the build-up of surface contaminants which render the particle less floatable.

Studies at both Leinster Nickel in Australia (Warder and McQuie, 2005) and Echo Bay Minerals in Canada (Jennings and Traczyk, 1988) found that flash flotation improved plant recovery by reducing the overgrinding of gangue minerals. Overgrinding of the gangue produced slimes which were noted by Jennings and Traczyk (1988) to coat the surface of valuable minerals and render them hydrophilic. The improved recovery after the commissioning of flash flotation at Echo Bay Minerals was not only attributed to the reduction of slime particles but also the limited contact time in the flash flotation cell.

2.9.4 Increased Throughput, Plant Stability and Metallurgical Efficiency

As noted by Newcombe et al. (2012b), implementation of flash flotation can reduce both cost and complexity in a mill by treating large volumes of material in a single vessel with a small footprint. Not only does flash flotation remove liberated

target material within the milling circuit which helps prevent buildup of the circulating load, it also reduces the amount of material being reground leading to cost savings in energy, reagents, capital and operations. It has also been suggested that flash flotation is beneficial to conventional flotation in two ways. Firstly, it allows the conventional flotation circuit to operate more efficiently by helping to minimise the impact of surging and secondly, it allows the conventional flotation circuit to target the harder to float particles.

2.9.5 Water Balance/Dewatering Benefits

The concentrate product of flash flotation is of a coarser size distribution than conventional flotation concentrate (primarily as a function of the feed material, considering most of the mass content in the concentrate is gangue), and consequently is easier to thicken and filter in comparison to finer material. Of primary concern to the plant, however, is the water addition required to float a high solids density stream like the cyclone underflow, while attempting to maintain the water balance of the milling circuit. Some authors (Newcombe et al., 2012b) and plant personnel alike have commented that the hardest part of a flash flotation operation is maintaining the correct water balance; too little water is bad for flotation performance while too much water impedes comminution. SkimAir® vessels have attempted to combat this by use of the dual outlet system to allow removal of fines and excess water from the top outlet while the dense slurry formed from the coarse particle outlet at the bottom of the vessel is well suited to return to the mill for regrinding. The top or fines outlet is a dilute stream of material that is typically around feed grade, consisting of fairly fine particle sizes, and about 5-25% solids concentration (this varies slightly depending on site specific requirements). The fines outlet product is normally sent straight to the mill discharge hopper and hence the stream, which is mostly water, bypasses the mill. This design is the basis for maintaining a higher solids density at the bottom outlet, which is preferable for milling efficiency. The attractiveness of having a top outlet is that enough water can be added to the flash flotation feed to get the solids density down to optimal flotation performance while maintaining a high density bottom outlet product necessary for grinding efficiency.

2.9.6 Effect on Downstream Processes (Carbon and Conventional Flotation)

Although flotation can have a negative impact on surface chemistry of both gold and activated carbon particles in downstream carbon-in-pulp (CIP) processes (Laplante and Gray, 2005), the impact of a flash flotation circuit within the mill upon conventional flotation can be advantageous and, if conventional flotation is already in the process flowsheet, flash flotation would not be expected to make any additional contribution to carbon fouling. Flash flotation by design scalps the readily floatable material, reducing the required recovery by subsequent conventional flotation while overall plant recovery is actually increased. Flash flotation also buffer plant surges to deliver a more stable feed to the conventional float circuit, where additional reagents may then be required to recover the less floatable material (MacKinnon, 2002).

2.10 Disadvantages of Flash Flotation for Free Gold Recovery

The benefits of flash flotation cannot always be readily recognised, especially when the circuit has been introduced at the design stage and there are no historical data for comparison, as in the case of a retrofitted mill. However, it is understood that the unit can have several consequences, not only upon behaviour in the milling circuit, but for downstream operations as well. As with conventional flotation, flash flotation performs best with stable feed material and optimised operational parameters. Operation of the flash flotation unit within the milling circuit requires operators and metallurgists to be both knowledgeable and attentive, and it is helpful to have dedicated staff to monitor performance.

2.10.1 Froth Requirements

Due to the nature of slurry being fed to the flash flotation unit, the froth required to combat gravitational forces which can disrupt the bubble-particle agglomeration must be strong and stable. Not only is froth stability related to aeration rate and frother type and concentration, but it has been shown to be tied to

the nature and concentration of the particles being floated as well (Farrokhpay, 2011). Feng and Aldrich (1999) demonstrated froth stability is influenced by particle size with medium sized particles contributing to a more stable froth than coarse or fine materials. Seaman et al. (2006) validated the selective nature of particle froth drainage in an industrial setting by demonstrating that coarse/dense particles are more likely to detach and drain back into the pulp after being recovered to the froth than their finer/lighter counterparts.

The height of a stable froth has been correlated to the size of particles contained within by Farrokhpay (2011), revealing smaller particles build deeper froths while coarse particles are only supported in shallow froths. This explains why cleaning applications employ thicker froths, while thinner froths are more prevalent in rougher type circuits. Although it is quite stable, the froth thickness in flash flotation is notably thinner than that of conventional flotation due both to the coarseness of the particles and low reagent dosage levels intended to minimise the impact on downstream flotation. The thin froth layer makes the cell prone to ‘pulsing’, where slurry (not concentrate laden froth) flows over the lip of the vessel into the launder (MacKinnon, 2002) resulting in dilution of the concentrate grade. Validation from various studies (Kallioinen and Heiskanen, 1993; Ross, 1990) confirms that coarse particle recovery decreases with increasing froth depth, offering justification of the shallow froth operating strategy for flash flotation.

Flash flotation concentrates may be added to the concentrate produced by conventional flotation or used as a feed stream to another unit operation. Processing options include regrind/leach, roast/leach, pressure oxidation/leach or biological oxidation/leach. Each of the downstream processes requires a stable feed grade and composition to operate ideally, with some processes being more sensitive to certain components than others.

2.10.2 Sensitivity to Feed Density

Ball mill discharge and cyclone underflow streams, which are essentially flash flotation feed material (with an oversized +600 μm fraction), are high solids

density streams. When the material is above the desired limit of 65 % solids in the slurry, it cannot be directly used as flash flotation feed. As previously mentioned, flotation of any constituent other than gangue is generally not efficient at such high pulp densities. Even though the case of increased pulp density for improved free gold flotation has been made by various researchers (Klimpel, 1999; Leaver and Woolf, 1934; MacKinnon, 2002), others (Lins and Adamian, 1993) have suggested a lower solids density within the pulp would promote free gold flotation. Regardless, the 65% solids in the mill discharge or cyclone underflow is too great for the targeted 45% solids in the flotation zone of the flash flotation cell so the feed must be diluted in order to optimise recovery.

The flash flotation vessel design gives a pulp density gradient within the cell. Because large particles tend to sink, in the bottom section of the vessel experiencing classification, there is a much higher pulp density in the conical lower region in comparison to the top area where flotation occurs. This density profile helps combat the high pulp density of the feed material while limiting the amount of dilution water required.

2.10.3 Maintenance Issues

Maintenance requirements of a flash flotation cell can be considerably greater than for conventional flotation cells. Fortunately there is usually only one cell (or small group acting as rougher and cleaners) as compared to the multiple banks of cells required in conventional flotation. The high maintenance requirements are due to the abrasive nature of the flash flotation feed; because the cell treats coarse particles in a high pulp density slurry with a large throughput (low residence time), the wear and tear on the vessel and rotor/stator mechanism is significant. In addition, the unit may need to be taken off line periodically in order to clear the cell of accumulated ball mill scats and coarse particles unable to leave through the outlets (MacKinnon, 2002).

2.11 Available Flash Flotation Technology

O'Connor and Dunne (1994) stated that the most interesting development in flotation was the application of Skim Air® flotation cells for free gold recovery. The authors reports several sites have noticed a dramatic increase in free gold recovery with the installation of SkimAir® cells. SkimAir® vessels were conventionally fitted with a SkimAir® specialised style rotor, though new and retrofitted vessels may now feature the FloatForce© mechanism. Both designs have been created to minimised wear in coarse particle agitation, with improved bubble flux area and air-hold up volume listed as additional key benefits for the FloatForce® innovation (Outotec, 2014).

Researchers have also suggested that the use of column cells within the milling circuit could be advantageous to the recovery of gold because the quiescent pulp allows for more efficient use of selective collectors and conditioning gases, such as nitrogen and sulfur dioxide (O'Connor and Dunne, 1994). While a few operations use column cells for flash flotation applications, for example Bulyanhulu in Tanzania (Barrick) and the Phoenix mine in Nevada (Newmont), the mechanical design is more common.

2.12 Combined Gravity and Flash Flotation

Free gold can report to many unit operations, be it gravity, flash flotation, conventional flotation, or leaching, but at added cost for recovery as it travels downstream. Flash flotation can be used in parallel, series or cleaning arrangements with BCC units for recovery of free gold within the milling circuit. Various examples of common configurations with cyclone underflow as the feed stream are depicted in Figure 2-16.

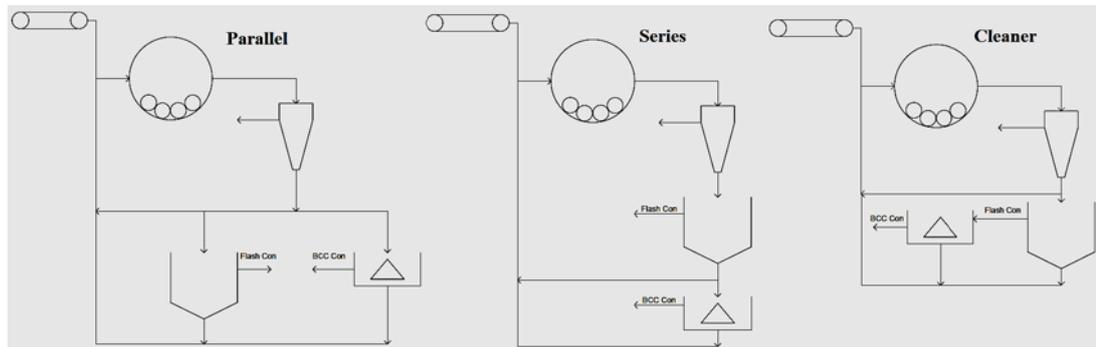


Figure 2-16. Possible flash flotation and BCC arrangement in a simplified milling circuit

In a cleaning application, flash flotation creates a sulfide concentrate which is then secondarily treated by gravity recovery for removal of GRG from the bulk sulfide concentrate. In series, the BCC treats a portion of the flash flotation tails. In the parallel configuration, the flash flotation and gravity units share the same feed and the tails streams are returned to the milling circuit to close the loop. Often cyclone underflow is selected for feed to both flash flotation and gravity but Laplante and Gray (2005) suggest any of the streams within a circulating load can be targeted. Feed from the ball mill will have the highest grade and liberation of GRG while the cyclone feed stream is often the most cost effective, minimising the cyclone height and number of pumps required.

The use of parallel BCC and flash flotation processes in a closed loop milling circuit is an option that many operations with complex ores containing both free gold and gold contained in sulfides may choose to employ to collect the gold as early in processing as possible. In general, when the GRG content is high and the size fraction is coarse, free gold is easy to recover and concentrate in gravity operations. BCC units ideally operate to concentrate coarse free gold particles larger than 106 μm . Some recovery of particles between 106 and 38 μm is attained, but it is variable and dependent on factors such as particle shape and operational parameters. BCC systems poorly recover gold particles smaller than 38 μm (Laplante and Staunton, 2005). Despite the ideal particle-size gravity gold recovery curve presented for BCC's in Figure 2-17, Wardell-Johnson et al. (2013) have shown that the size-by-

size recovery of GRG is far from an ideal monotonic function, with actual BCC devices often showing a U-shaped curve (rather than a monotonically increasing S-shape) for intermediate particle sizes. As demonstrated in Figure 2-17, a parallel type of arrangement is both complementary and competitive.

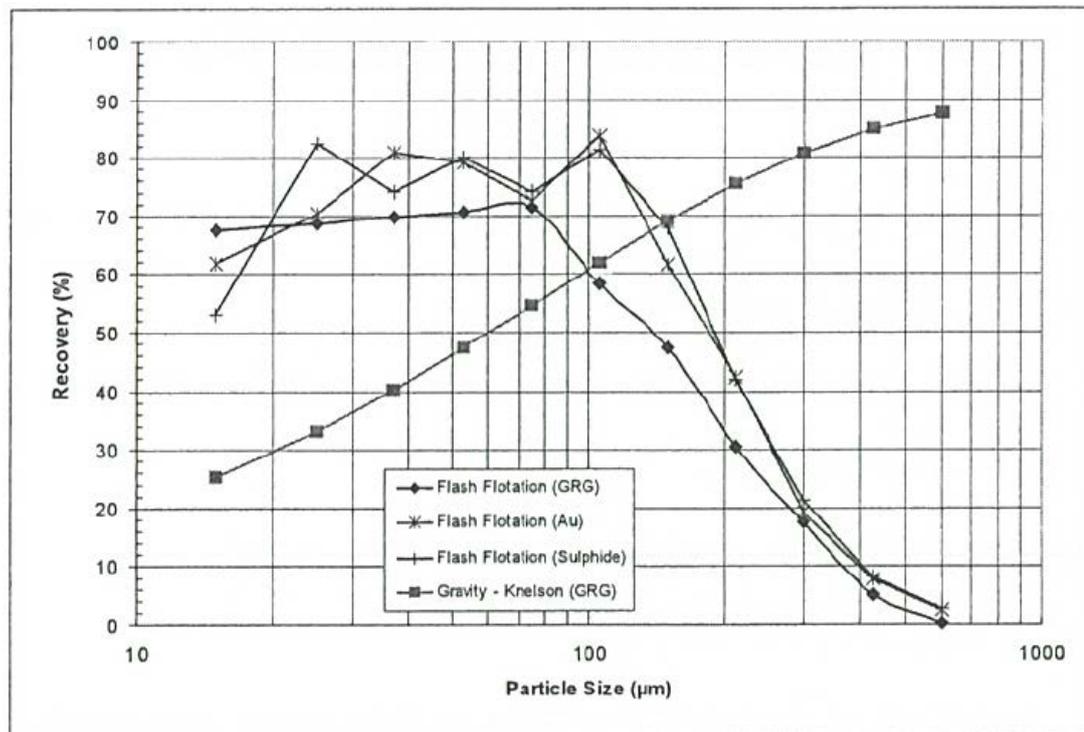


Figure 2-17. The particle size interaction of flash flotation and gravity concentration (Curtin University Gold Technology Group, 2008)

Competitively, both the gravity and flash flotation circuits are capable of recovering particles in the range of 106 to 37 µm. They are complementary in the sense that the gravity circuits will perform best at recovering particles of free gold larger than 106 µm and the flash flotation circuit will best recover free gold and unliberated sulfide particles smaller than 38 µm. For additional discussions on the gravity/flash flotation relationship, the reader is directed to Laplante and Dunne (2002a), Laplante (2005) and Bourke (2002). Though particle size is of great importance, the ability of free gold to be recovered or become a part of the

circulating load in a mill with a gravity circuit is complex, and most likely dependent on many factors.

2.13 Summary

The literature review has highlighted several significant areas requiring clarification in order to understand the recovery of free gold in a milling circuit containing flash flotation and gravity recovery:

The key variables for consideration for development of the laboratory free gold flash flotation test are:

- What are the effects of collector (PAX) and activator (copper sulfate) reagent additions on a free gold ore which does not contain sulfide material?
- What are the causes of the varied flotation responses for similar sized particles with differing genesis and residence time?
- In addition, can readily available characterisation techniques (QEMSCAN and Micro CT) be used to identify physical differences, specifically shape, in particles captured at various points during a survey of flash flotation and gravity circuits?

Based on the literature review, the objectives of this study are:

1. Develop a robust and repeatable bench scale flash flotation test (the Free Gold Flash Flotation Test) to determine the maximum free gold recovery. The free gold particles which are recovered in this test represent the ultimate FRFG content. The method will:
 - a. Be repeatable,
 - b. Distinguish free gold from gold in sulfide carriers,
 - c. Determine whether or not the test can be conducted on dry plant samples, and

- d. Provide conditions which maximise FRFG recovery across the possible range of physical and chemical factors known to affect recovery of free gold in flotation. This type of information previously existed in an anecdotal form but will now be demonstrated with the laboratory testwork.
2. Investigate the response of free gold of differing genesis in key size classes (coarse, intermediate and fine) to changes in collector dosage.
3. Determine the recovery behaviour of free gold in an industrial setting with gravity and flash flotation operating in parallel, with an emphasis on the influence of size and shape.
4. Evaluate the accuracy of stereological measurements from existing techniques for the quantification of free gold shape by comparing two and three dimensional (2D and 3D) methods and identifying the limitations of these applications.

CHAPTER 3. EXPERIMENTAL METHOD

The literature has highlighted a lack of understanding of the factors affecting the recovery of free gold to either flash flotation or gravity recovery devices within a closed loop milling circuit. While research on gravity recovery processes have generally concentrated on free gold, the limited data published on flash flotation circuits are focused on sulfide minerals. The proposed Free Gold Flash Flotation laboratory test will define the Flash Recoverable Free Gold (FRFG) content of an ore and can be used to study the effect on recovery by changes made to reagent schemes, operational parameters and feed material.

3.1 Materials

3.1.1 Silica

Two types of Silica were used as the gangue component of the synthetic ore used for laboratory testwork. The first, Silica 200 Mesh, purchased from Sibelco in Welshpool, Western Australia, was used as quarter of the composite and represents the -75 μm component. The coarser second fraction, Superfine, purchased from Cook Industrial Minerals PTY LTD in Jandakot, Western Australia, made up the remaining three quarters of the blend.

3.1.2 BCC Concentrate

A BCC concentrate sample was used in some synthetic ores a source of free gold. The BCC concentrate (P_{100} of 600 μm) was created by blending multiple concentrates of laboratory Knelson testwork with primarily Australian ores.

3.1.3 Gold Powder Particles

Some synthetic ores contained free gold as pure gold purchased from Sigma Aldrich in the United States. The gold powders (product numbers 14641, 44882 and 43901) were blended together in equal parts to achieve the desired distribution of particle size and shape.

3.1.4 Pyrite

A mineralogical sample of pyrite, free of gold, was purchased from The Gemstone Factory in Orange Grove, Western Australia. The sample was milled to - 212 μm for use as the sulfide component of the synthetic ore.

3.1.5 Plant Samples

Three site surveys were conducted to collect the samples for testwork in Chapter 6. The samples were taken at Telfer (Western Australia, January 2013), Kanowna Belle (Western Australia, June 2013) and Tongon (Côte d'Ivoire, July 2013). The Telfer and Tongon surveys were conducted by the author and other researchers in the AMIRA P420 group, respectively. Kanowna Belle was sampled by employees on site. Samples from all sites were received dry and individually bagged to prevent contamination. The concentrates were wet screened at 600, 212 and 38 μm and dried at 70° C overnight before further processing.

Tongon Mine

Tongon is operated by Rangold in the Côte d'Ivoire. According to Vaughan (2013), the Tongon deposit is an orogenic gold ore located in a Birimian-aged (Proterozoic) sequence in northern Ghana. Host rocks to the gold deposit are greenstones dominated by a quartz-carbonate-amphibole-pyroxene-feldspar assemblage. Gold mineralisation is hosted by arsenopyrite, pyrite and pyrrhotite, with minor loellingite and chalcopyrite. Gold is predominantly free milling with a small refractory component associated mainly with arsenopyrite and loellingite. Native gold in the ore is relatively fine-grained ($\leq 50 \mu\text{m}$, averaging about 10 - 20 μm), and mostly contained as fine-grained inclusions in arsenopyrite and loellingite.

The site operates two processing trains which are identical and receive the same feed material. In each, the cyclone underflow is roughly split three ways; flash flotation feed, Knelson feed and a return stream to the mill. Tongon had no conventional flotation at the time of the survey in July 2013, although the site has

Figure 3-1. Tongon Milling Circuit

Kanowna Belle Mine

Kanowna Belle was operated by Barrick at the time of the survey, although ownership has recently shifted to Northern Star Resources LTD. Vaughan (2013) summarised Kanowna Belle as a greenstone-hosted orogenic gold orebody located in the Archean Eastern Goldfields province of Western Australia. Locally the orebody is hosted by microfractures, veins and disseminations in a sequence of volcanoclastics, conglomerates and felsic porphyries. The main ore minerals are pyrite, lesser arsenopyrite and native gold. The ore is refractory and is related mainly to the presence of solid solution gold and fine-grained inclusions of native gold in pyrite and arsenopyrite.

The mill processes material from various pits at any given time so the flash flotation and gravity units are operated based on the requirements of the feed material. Sometimes the mill runs flash flotation only, sometimes gravity only, but at the time of the survey the two units were being operated in parallel for the first time in the plant's history and the crew onsite had already spent many weeks trying to achieve stable operation prior to the survey in June 2013. At Kanowna Belle, the flash flotation concentrate is combined with conventional flotation concentrate then roasted to treat the refractory gold component prior to leaching. The gravity concentrate is subjected to intensive cyanidation. No GRG determination had been performed on the ore blend sampled during this campaign. A simplified process sheet for the parallel arrangement is given in Figure 3-2, although the top discharge outlet was not operating during the time of the survey.

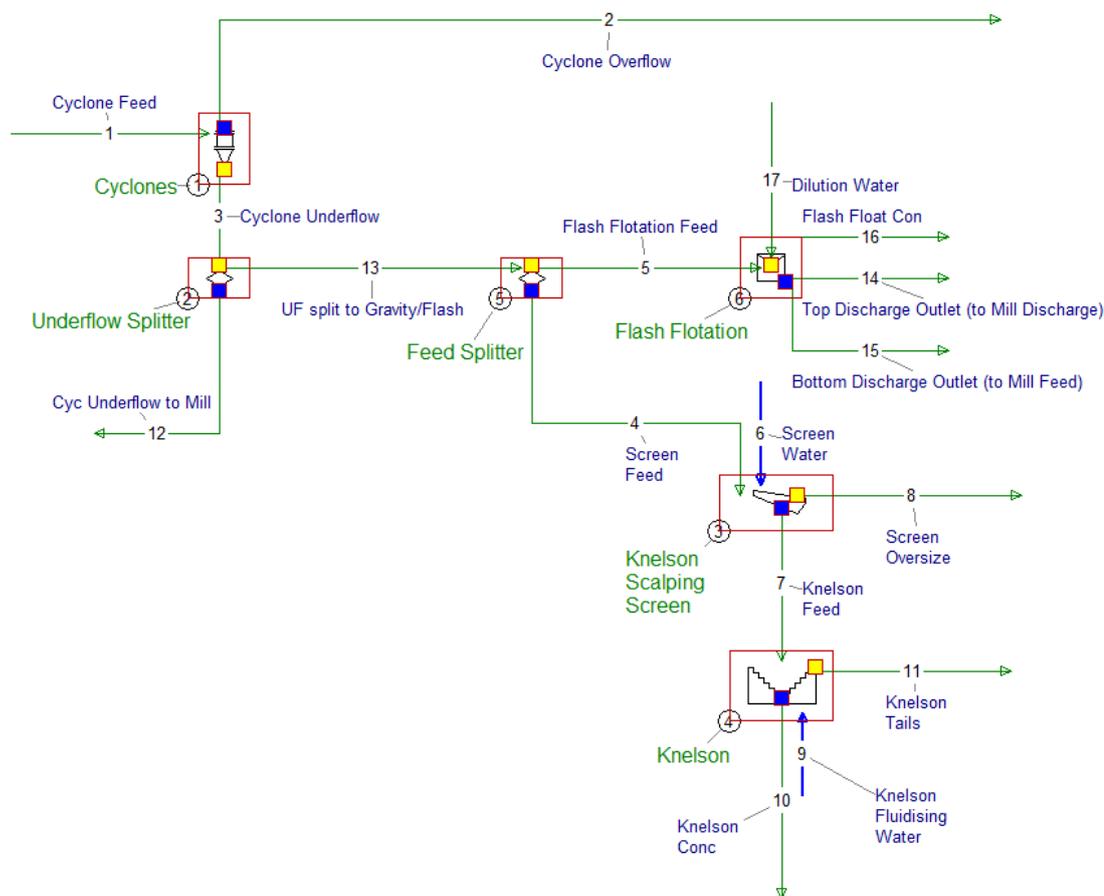


Figure 3-2. Kanowna Belle Milling Circuit

Telfer Mine

As reported by Vaughan (2013), the Telfer gold mine, owned and operated by Newcrest, is a Proterozoic copper-gold orebody located in the Great Sandy Desert of Western Australia. The ore is stratabound within a weakly metamorphosed sequence of calcareous and carbonaceous siltstones. Primary mineralogy is dominantly pyrite, chalcopyrite, pyrrhotite, minor cobaltite and native gold. There is extensive supergene enrichment in the upper parts of the orebody, with the development of secondary chalcocite, covellite and other secondary copper minerals.

The mill has two parallel processing trains which were receiving the same feed at the time of the survey in January of 2013, although usually one of the trains

(train 1 or T1) processes underground feed containing a higher proportion of free gold in combination with the open pit ore common to both trains. The mill discharge is split to two separate cyclone clusters; one feeds the flash flotation unit while the other is directed to four BCCs, Falcons in this case. The Falcon concentrate is upgraded on tables prior to production of bullion and an intermediate high grade concentrate product while the float concentrate is sold to smelters as a copper concentrate which is credited for its gold value. A recent survey suggests that the GRG content of the open pit ore is 17.9 % of the total gold with 24.7 % of the GRG being less than 75 μm (Wardell-Johnson and Bax, 2012b). The site achieves fairly good recoveries via the Falcons, although the flash flotation generally performs more poorly than what could be reasonably expected from this site. A flowsheet of Telfer T1 is provided in Figure 3-3.

3.1.6 Flotation Reagents

The flotation reagents PAX and MIBC were supplied by Orica in Perth Western Australia. Copper sulfate pentahydrate (AR grade) had been previously purchased from Rowe Scientific in Perth, Western Australia and was available for general use in the laboratory.

3.2 Synthetic Ore

Synthetic ores were created for laboratory testwork to evaluate the flotation response of free gold in a GRG concentrate containing leachable gold as a starting point to understanding the FRFG content of GRG. The simple, synthetic ore formulation was a mixture of silica gangue, gold (either from the BCC concentrate or as pure gold powder particles) and sometimes, a sulfide source (pyrite). The main component, silica sand, present in a size distribution representative of the -600 μm fraction of a typical flash flotation feed, was added as required for 1 kg total charge.

3.2.1 Formulation for FRFG Determinations

The mixed BCC concentrate is the only gold source for the synthetic ores used in the testwork presented in Chapter 4. The BCC concentrate material was split into 5 g subsamples which were added to the silica gangue to form the combined feed material with average head grades of 13-16 g/t. Because the GRG concentrate contributed very little sulfide (0.08% S in 1 kg) to the laboratory test charges, as compared to percentages seen in typical flash flotation feeds, tests requiring a 5% sulfide component also included pyrite (P_{100} of 212 μm , containing no gold) additions to act as a sulfide source. Synthetic ore masses for the silica/BCC concentrate/ pyrite synthetic ore system are tabulated in Table 3-1.

Table 3-1. Chapter 4 Synthetic ore compositions

		Mass of component (g)		
		Silica	BCC con	Pyrite
Synthetic ore type	0% Sulfide addition	995.0	5.0	0.0
	5% Sulfide addition	901.5	5.0	93.5

In order to refresh the surface of the BCC concentrate in the synthetic ore, a dry refresh technique was tested. The simple procedure involved rolling the dry synthetic ore in a 2 L plastic bottle over a period of time to determine if FRFG recoveries would be improved as indicated by cyanide leach recoveries (further detail given in Appendix 9.1 and 9.2). Improvement in free gold recoveries would suggest dry sample storage for free gold flotation testwork is inadequate and samples would need to be stored in a freezer and/or freshly ground prior to laboratory flotation as done in sulfide testwork.

3.2.2 Formulation for Studying the Effect of Collector Dosage and Gold Genesis

In the second set of laboratory experiments presented in Chapter 5, gold from two sources was floated according to the Free Gold Flash Flotation Test with variations of PAX addition and gold type being the only manipulated variables. These experiments were designed to compare trends in flotation kinetics for particles of varying size and nature as affected by the addition or absence of a collector. The first of the synthetic ore samples was created identically to the ores used in Chapter 4 for determining the flash flotation procedure. A bulk assay of the BCC concentrate suggested particles in the concentrate had a 9:1 ratio of Au to Ag, although SEM (Scanning Electron Microscopy) has shown individual particles varied in that ratio and types of elemental distribution (Appendix 9.3). Images of particles typically found in the GRG concentrate are shown in Figure 3-4. Note the measurement bars each represent 100 μm .

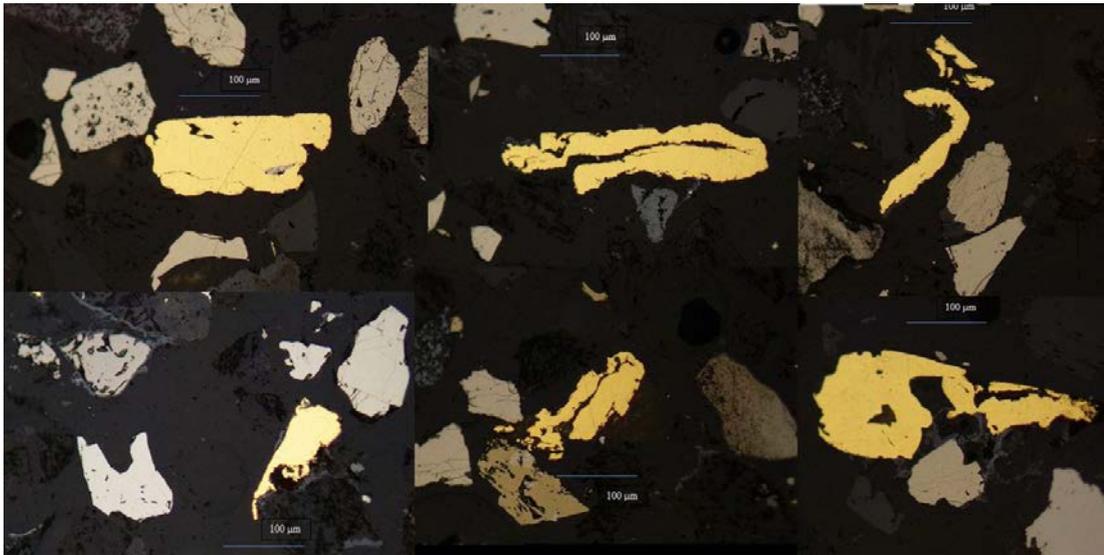


Figure 3-4. Gold particles in the GRG concentrate

The second synthetic ore, tested in Chapter 5, was created using the same silica blend as the first but used synthesised pure gold powder particles (P_{100} 250 μm), with a head grade of 30 - 40 g/t. Images of typical gold powder particles produced by amalgamation and precipitation can be found in Figure 3-5. Again, the measurement bars represent 100 μm .

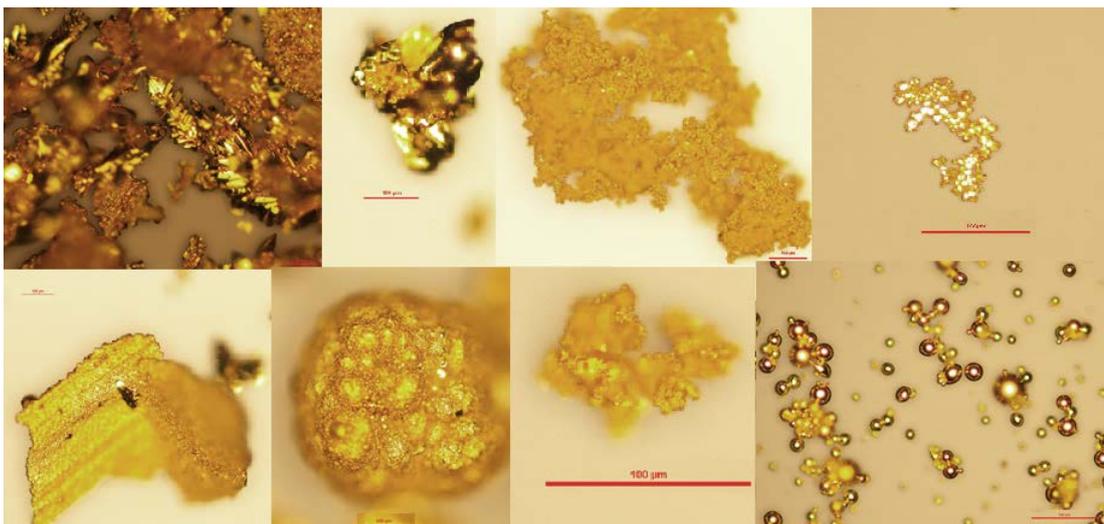


Figure 3-5. Au particles in the powders

In Chapter 5, the laboratory tests were repeated on 1 kg charges six times for each of the six conditions in order to produce enough combined concentrate mass to be screened into the three size fractions of interest. The repetition of testwork also ensures that average mass and concentrations reported are statistically sound measurements. Each set of six conditions produced seven concentrates and a tails sample, all of which were screened into three size fractions (+212, +38 and -38 μm), yielding 21 samples per test or 147 for the entire data set. It is important to note the differences in feed size distribution for the different gold sources, as tabulated in Table 3-2, which demonstrates the coarseness of the BCC material as compared to the synthetic gold.

Table 3-2. Average feed size distribution for gold contained in the synthetic ores

	Au Powder	BCC Concentrate
Coarse (+212 μm)	12%	18%
Intermediate (-212/+38 μm)	35%	67%
Fine (-38 μm)	53%	15%

3.3 Determination of Free Gold Content by Cyanidation

Intensive cyanidation was used to determine the free gold content of the flash flotation concentrate and tails in the flotation testwork for Chapter 4. This is particularly necessary when the test is applied to real ore systems, whose gold is deported in several minerals as compared to the synthetic ores which were shown to contain only free gold.

In order to determine the method and required time for leaching the flash flotation concentrate, five replicate samples were subjected to intensive cyanidation. The 5 g samples consisted solely of the BCC concentrate used in the creation of the synthetic ore, though it resulted in an abnormally low 1% solids content for this testwork. The 5 g of BCC concentrate is the theoretical maximum that any flotation

concentrate could contain in the first series of testwork so this ensures all experimental samples would be leached under similar conditions. Figure 3-6 demonstrates leaching was complete within 10 hours and the differences in the rate of leaching are insignificant.

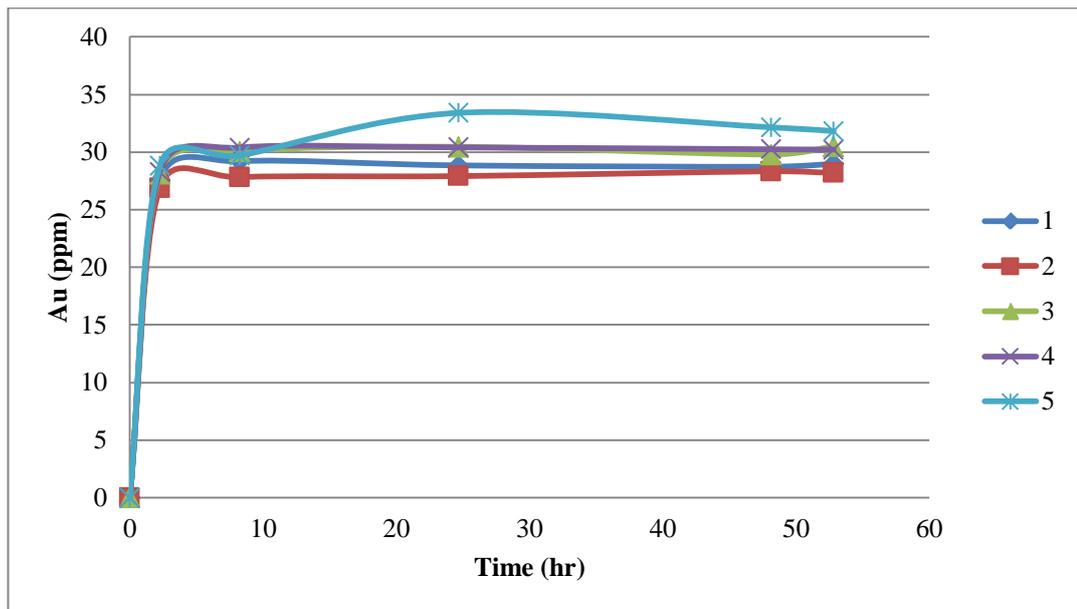


Figure 3-6. Concentrate leaching kinetics (100 rpm, 3 g/l NaCN, pH 10.5)

The leach residues were then dried and sent to UltraTrace (a division of Bureau Veritas, in Canning Vale, Western Australia) for fire assay to determine if there was any refractory or unleachable gold contained in the concentrate at the end of cyanidation ($T_f = 50$ hrs). At the same time, four BCC concentrate samples were also sent to SGS Laboratories (Newburn, Western Australia) for fire assay to determine an average head grade and offer a comparison to the calculated head grade from atomic absorption spectroscopy (AAS) of the leach liquors. The gold assay results are presented in Table 3-3 and, on average the BCC concentrate was shown to have a 9:1 ratio of gold to silver as determined by AAS.

Table 3-3. Concentrate assay results (averages)

Sample	Average Au (ppm)	Method
BCC Concentrate	2669	Fire Assay, AAS
Leach Liquor @ T _f	2905	Cyanidation, AAS
Leach Residue	1.5	Fire Assay, ICP-MS

The low gold content in the leach residues indicates that nearly all of the gold in the BCC concentrate was leachable (therefore by definition “free gold”) and this cyanidation method is sufficient to dissolve the contained gold. The reasonable agreement of the average values of gold contained from the two methods suggests they are comparable and can be used interchangeably.

For all samples produced during the FRFG determination testwork in Chapter 4, gold recovery was determined using the cyanidation bottle roll standard operating procedure (SOP, given in Appendix 9.2) using entire concentrate samples or one quarter splits of tails samples. The head grade for individual samples was then calculated by difference. Significant error in the calculated head grade and assayed head grade would be indicative of sampling or abnormally high experimental error, though it was not experienced in this set of testwork.

Flotation concentrate samples created during the second set of laboratory tests in Chapter 5 were fire assayed to extinction while 30 g splits of the tails samples were subjected to fire assay and 300 g splits were leached via cyanidation bottle roll. The previous analysis of the BCC concentrate confirmed that the contained gold is not refractory, meaning fire assay and leaching results should both report the same gold content, so cyanidation on the larger splits of sized tail samples allowed for better closure of the mass balances. The mass of gold in the test was either known, in the case of the powder, or calculated, in the case of the concentrate, so inconsistencies in the gold and mass balances can be attributed to the nugget effect in the coarse, and to some extent, the intermediate tails samples. (The nugget effect compromises the ability to achieve representative grade or concentration results due

to non-uniform distribution of gold in the assayed sample as compared to the bulk material. The impact of the nugget effect is most noticeable in the precious metal assays of coarse size fractions and small sample size, yielding highly variable values.)

3.3.1 Equipment

A custom 2 L vessel (Figure 3-7) was designed for use in the Outotec laboratory flotation machine (Figure 3-8) fitted with the Float Force[®] rotor and stator design (Figure 3-9) for all laboratory flotation testwork.

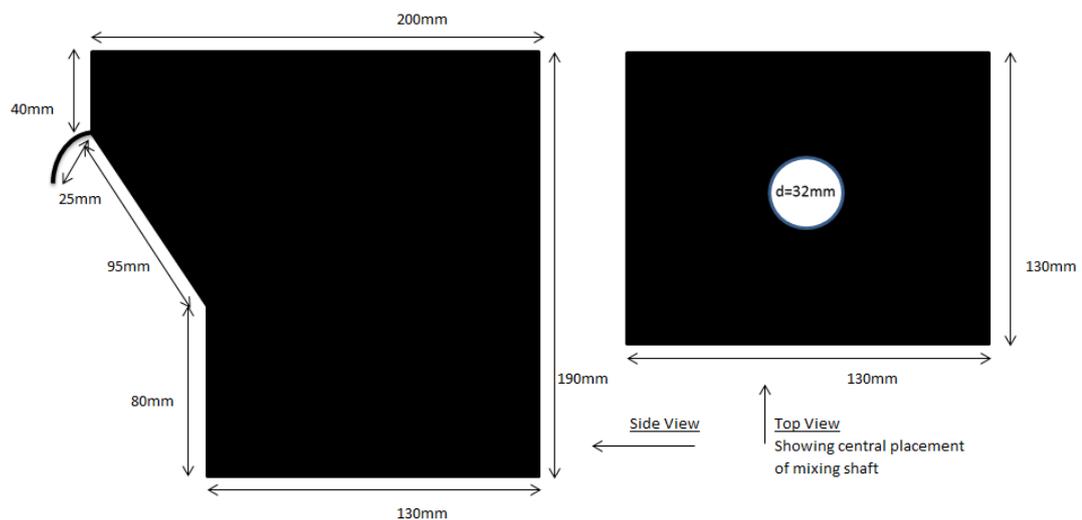


Figure 3-7. Design template for 2 L flash flotation vessel used in laboratory testwork



Figure 3-8. Outotec laboratory flotation machine shown with custom vessel and scrapers



Figure 3-9. Laboratory scale FloatForce[®] rotor (left) and MultiMix[®] rotor (right)

It is important to note that operational and mechanical factors for laboratory scale testing were determined based on responses unique to this flotation setup. Because of this, parameters given will yield varying results depending on equipment used but the trends observed would still apply. In the past, all of Outotec's industrial SkimAir[®] flash flotation cells and laboratory flotation machines were fitted with a MultiMix[®] rotor/stator mechanism (the laboratory version is also shown in Figure 3-9). The experimental setup used in this testwork was unique because, at the time of writing this thesis, the FloatForce[®] mechanism, the newest impeller innovation marketed by Outotec, was the only one of its kind in used outside of the Outotec laboratories. A size comparison of the two rotors is given in Table 3-4.

Table 3-4. Laboratory rotor comparison

	MultiMix [®] Rotor	FloatForce [®]
Top Plate Diameter	39 mm	52 mm

Different styles of rotor/stator produces different hydrodynamic conditions, adding another variable preventing direct applicability of the laboratory work to

industrial systems or comparison between systems. The FloatForce® is specifically designed to maintain the suspension of coarse and dense particles in a high solids slurry which often experience “sanding” or particles settling out in standard flotation machines. Sanding is particularly an issue in bottom driven machines or those with fixed stators because the trans-axial flow is hindered and attachment points of the rotor/stator mechanism to the vessel cause a build-up of material.

3.4 Kinetic Models

Analysis of flotation performance is often conducted through various kinetic models, the type of which being dependant on the kinetic rate order and the components of interest. The first order rate equation for batch flotation is generally described by the following differential Equation 6:

$$\frac{dC}{dt} = -kC \quad 6$$

Where:

k = kinetic rate constant,

C = concentration of the floatable material in the pulp at time = t , with all other variables being held constant.

Brezani and Zelenak (2010) point out that flotation is a process which is affected by many properties, not just physico-chemical and surface properties, but many other chemical operational and mechanical factors as well. It is because of this complexity that flotation is often described as a simplified first order kinetic phenomenon (Kelly and Spottiswood, 1989) demonstrating a two component (floating and nonfloating) system. The first order rate reaction is derived by integration of Equation 6 and can be expressed in terms of recovery (R) as follows in Equation 7:

$$\mathbf{R = 1 - \exp(-kt)} \quad \mathbf{7}$$

Kinetic rates have also been calculated for each size fraction in all data sets of this study using the modified Kelsall approach, as presented in the following equation, which designates fast, slow and nonfloating components in the slurry. Although this method was developed many years ago (Kelsall, 1961) its continued relevance has been evaluated by various authors (Brezani and Zelenak, 2010; Kelebek and Nanthakumar, 2007; Kelly and Spottiswood, 1989) throughout the years and, in a similar study, it was recently applied to evaluate the kinetics of sulfides in flash flotation (Newcombe et al., 2012a) as demonstrated in Equation 8:

$$\mathbf{C = C_o[\alpha + \beta \exp(-k_s \cdot t) + \gamma \exp(-k_f \cdot t)]} \quad \mathbf{8}$$

Where:

C_o = the original concentration in the pulp,

C = the concentration in the pulp at time = t ,

t = elapsed time in the duration of the experiment (min),

k_f = rate constant for fast floating material (min^{-1}),

k_s = rate constant for slow floating material (min^{-1}) and

α , β and γ = coefficients used to fit data for non-floating (\emptyset), slow floating (s) and fast floating (f) material, the sum of which equals one.

In this study, different kinetic parameters are compared by the following methods:

1. Two component (simplified first order reaction rate) ,
2. Three component with fixed ratio between k_f and k_s (where $k_f = 2k_s$) and
3. Three component (modified Kelsall).

The Akaike Information Criterion (AIC) is used to select the optimal model for the data set. A minimised AIC value indicates the model that best fits the experimental data taking into account a penalty factor for the number of adjustable parameters within the model (Akaike, 1974). The AIC is calculated as by Equation 9 follows:

$$\text{AIC} = N \cdot \ln \left[\frac{1}{N} \sum_{t=1}^N e^2(t) \right] + \gamma \cdot q \quad 9$$

Where:

N = number of data inputs,

e^2 = normalised error determined by $e(t) = [(Y(t) - \bar{Y}(t)) / Y(t)]^2$,

$\bar{Y}(t)$ = model estimated value of measured value $Y(t)$,

$\gamma = 5$, to decrease over parameterisation (Kanjilal, 1995) and

q = number of adjustable parameters.

Assessment of each model's fit to individual experiments is made by analysis of the mean absolute percentage error (MAPE) in Equation 10 which represents a measure of accuracy for each data set; this is a common method for determining forecast error in timed data series.

$$\text{MAPE} = \frac{100}{N} \sum_{t=1}^N \frac{|\bar{Y}(t) - Y(t)|}{Y(t)} \quad 10$$

While model fitting allows the estimation of ultimate FRFG content, recovery of all FRFG in a flash flotation cell would not be achieved industrially; primarily due to the short residence. Instead, with the measured rate constants from the kinetic studies, it is possible to predict the FRFG recovery in a given industrial cell based on its particular residence time.

3.5 QEMSCAN

QEMSCAN is a materials characterisation tool which uses SEM coupled with energy dispersive X-ray spectroscopy (EDS) detectors and data acquisition software to create maps of the elemental and mineralogical distribution of a specimen. Samples for the coarse, intermediate and fine material were prepared for QEMSCAN according to general CSIRO procedure. The sample preparation for this procedure is slightly different for the + 38 μm and the - 38 μm fractions. For the +38 μm fraction, samples were diluted with graphite (graphite size was similar to the smallest particles contained in the fraction) in three parts graphite to one part sample ratio in order to determine liberation and define particle edge characteristics. Particles in the -38 μm fraction were rolled out, mixed with -38 μm graphite, slurried in ethanol, sonicated and dried at to prevent particle agglomeration. Roughly two grams of the graphite/concentrate sample mixture was then mounted in epoxy, polished and carbon coated. The samples were analysed on QEMSCAN using a precious element scan mode to detect gold particles. Once gold has been detected the particle is then imaged and analysed for mineral composition. Very few (if any) gold particles were found in most samples, despite making additional scans of repeated mounts.

Due to the low free gold content of the initial QEMSCAN samples, a second set of samples was prepared according to the same procedure but with a 1:1 ratio of sample to graphite in order to increase the occurrence of gold particles in the sample. However, this technique still yielded too few particles for comparison and a MagStream™ was used to increase the sample density to roughly +6 SG, ultimately increasing the gold grade of the sample. Following application of the MagStream™ to all of the surveyed concentrate streams, the +6 SG intermediate sized samples were again prepared for QEMSCAN with a 1:1 ratio of graphite to sample. Although the manipulated samples were no longer representative of the stream in terms of grade, the concentrated gold particles could be evaluated for aspects such as particle size, shape (circularity as demonstrated in Section 3.7.1), surface area and elemental composition.

3.6 MagStream™

In order to further concentrate the gold particles as the target of image analysis, a MagStream™ unit was employed on splits of the -212+38 μm fraction from Telfer and Kanowna Belle. The MagStream™, which works to separate materials on a gravimetric basis as illustrated in Figure 3-10 (taken from the equipment brochure), was used as an alternative to toxic heavy liquid separations. Not only is this method safe it was also chosen so as not to bias the sample in selection of large particles which would likely happen in an attempt to reject gangue by a mechanical gravity separation method.

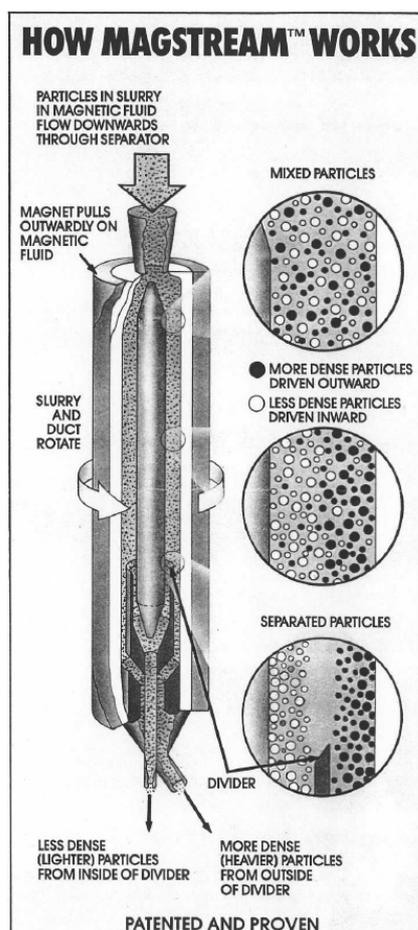


Figure 3-10. Illustration of MagStream™ operation as given in the equipment brochure (Intermagnetics General Corporation, undated)

Samples were pre-treated with a Frantz magnetic separator prior to MagStream™ to remove magnetic minerals present in the ore because ferro/paramagnetic minerals act like minerals of higher specific gravity (SG) in this system and will contribute to inefficient separations if not removed prior to the MagStream™ application. Some samples were first concentrated into +4 SG fractions and scrutinised under 100x magnification using a binocular style dissecting microscope. From this inspection it was determined that concentration of the gold particles was still insufficient at the +4 SG separation and more gangue material could be removed by making the cut at +6 SG instead. For Kanowna Belle and Telfer, the +4 SG fractions were separated at +6 SG, while the Tongon samples were only separated once at +6 SG.

3.7 Micro CT (X-ray Micro Computed Tomography)

Micro CT creates cross-sections of samples, generated by X-ray, to form 3D models. Micro CT of the survey samples was conducted at CSIRO Waterford in Western Australia using a Skyscan (now Bruker) Micro CT to obtain 3D images of gold particles and determine surface area and shape. The -212+38 µm fractions of +6 SG samples from each site's flash flotation and gravity concentrates were placed onto pedestal inside a plastic tube. The Micro CT scanner was calibrated with pure gold particles and generated, for each of the six samples, 3D images of gold particles with a 5.77 µm resolution. In addition to morphology from the 3D images, calculations of volume and surface area were made for each of the gold particles detected in the sample using the shape and sphericity calculations presented in Section 3.7.1.

3.7.1 Circularity, Sphericity and Volumetric Shape Factors

Shape has been identified as a factor likely to influence the recovery of free gold particles within the milling circuit. In order to determine two and three dimensional shapes for the free gold particles in the BCC and flash flotation concentrates, measurements made by QEMSCAN (2D) and Micro CT (3D) have been used to generate three descriptors for non-spherical particles; circularity (2D),

sphericity (3D) and volumetric shape (3D) factors. In the past, circularity and several other 2D shape factors have been used to describe the shape of mineral particles in metallurgical samples while the 3D factors of sphericity and volumetric shape were more common in drag calculations for the settling of particles in other fields such as pharmaceuticals, powders and lunar samples (Brown, 1991; Zeng, 2011).

Circularity (2D)

The circularity shape factor is an isoperimetric quotient or the ratio of the shape's area to the area of a circle with the same perimeter given by the following Equation 11:

$$f_{\text{circ}} = \frac{4\pi A^2}{P^2} \quad 11$$

Where:

A = area, and

P = perimeter.

A perfect circle would have an f_{circ} of one so a decrease in that value shows deviation from the most circular shape possible. Circularity was chosen as the method for 2D shape determinations because of parallels in measurement and description to the 3D shape factors calculated for the same samples.

Sphericity and Volumetric Shape (3D)

Sphericity, which is essentially circularity in 3D terms, was characterised by the United States Pharmacopeial Convention (USP) General Chapter method given by Zeng (2011). This method states that the simplest three dimensional shape is the sphere and other particles of irregular shape can be described as a measure of sphericity (Ψ), as given in Equation 12. It should be noted that sphericity is not always calculated in the same manner (Lin and Miller, 2005) nor is it always

represented by the same symbol; the method demonstrated in Equation 12 was chosen due to the existence of comparison data for ideal particles.

$$\Psi = \frac{6V}{dS} \quad 12$$

Where:

d = equivalent or nominal diameter of particle

S = surface area of particle

V = volume of particle.

Volumetric shape calculations are used to characterise a particle's physical properties and are used along with sphericity to describe the shape of irregular particles. The volumetric shape was calculated to make comparisons in similarity and consistency between the two 3D methods. The Heywood shape factor is a volumetric shape factor (Φ) calculated by Equation 13 (Brown, 1991).

$$\Phi = \frac{V}{d^3} \quad 13$$

Where:

d = projected diameter of particle

V = volume of particle.

CHAPTER 4. DEVELOPMENT OF A LABORATORY TEST TO QUANTIFY THE ULTIMATE FLASH RECOVERABLE FREE GOLD (FRFG) CONTENT OF AN ORE

4.1 Introduction and Background

Many methods exist for bench testing of sulfide flotation conditions; however none are specific to the flash flotation of GRG material and only a few have been published for flash flotation of sulfides (Lamberg and Bernal, 2009; MacKinnon et al., 2003; Newcombe et al., 2012a). Therefore, the first aim of this research was to develop a robust flash flotation procedure for FRFG determinations and evaluation of the impact of variables upon the recovery of FRFG. In addition to the published sulfide flash flotation methods several unpublished standard operating procedures (SOPs) and personal recommendations were provided by various commercial sources (ALS Ammtec, 2011; Flotation, 2011; Minnovex Technologies, 2011; Outotec, 2011; Systems, 2011; Telfer mine metallurgical laboratory, 2011) to serve as the basis for the Free Gold Flash Flotation test development. The suggestions provided were reviewed, altered and optimised for the repeatable recovery of free gold in ores of varying complexity.

Development of a test to repeatedly maximise free gold recovery required studying variables in reagent type and concentration, residence time (kinetics), operational/mechanical parameters, ore surface refreshment, and mineralogy. Response surface modelling, or RSM, is a powerful statistical tool in experimental design (implemented via Stat-Ease Experimental Design software, in this research) which was used to achieve the maximum amount of statistically significant information the flash flotation testwork while limiting the number of samples and associated tests (Anderson and Fayram, 2005).

In this chapter, a synthetic ore with a P_{100} of $-600 \mu\text{m}$ comprised of silica, BCC concentrate and sometimes pure pyrite additions (as a form of non-gold hosting sulfide) was used to simulate an industrial feed. The testwork studied the effect of collector (10 or 25 g/t PAX), frother (10 or 20 g/t), activator (0 or 20 g/t copper

sulfate), sulfide (0 or 5% addition), agitation (1000 or 1200 RPM), aeration (5 or 10 LPM), and a dry surface refreshment technique on the recovery of FRFG.

4.2 Results

4.2.1 Method Determination

Unplanned, unaccountable variation is detrimental in laboratory flotation work especially when the desired end use is model development, and flash flotation is no exception. Initial flash flotation tests were performed to identify which of the supplied current methods yielded greatest repeatability. As significant variability may already be introduced by differences in the ore, all other sources of variations should be minimised. The following section details the techniques evaluated for the development of the laboratory flash flotation test and offers the logic behind finalising the method for the Free Gold Flash Flotation Test.

Flotation Procedure

All slurries for laboratory flotation test were prepared with Perth tap water. No results were included in the data analysis for test conditions which produced sanding in the flotation vessel or an insufficient froth for scraping. Optimal reagent brands and dosage ranges were based on a literature review (Allan and Woodcock, 2001; Dunne, 2005; Klimpel, 1997; Klimpel, 2000; Monte et al., 2002; O'Connor and Dunne, 1994; Teague et al., 1999a; Woodcock et al., 2007), known industrial application and their availability for laboratory testwork. Reagents were added to an agitated slurry in a specific order (collector, activator, frother), with the addition of one reagent following immediately after the previous and a 5 s conditioning time between the last reagent addition and the initiation of the airflow. The commencement of air addition to the agitated slurry was considered the start of the experiment, $t = 0$ s. Froth collection began at the 5 s mark and continued as required by the collection method for the duration of the test.

Scrapers vs. Custom Paddles

Two types of tools, scrapers and paddles, were evaluated to scrape the surface of the froth and transport the laden froth to the collection tray. The scrapers evaluated were simple plastic spatulas (putty knives) purchased from a hardware store. These scrapers, or ones of similar design, are commonly used for flotation testwork in commercial laboratories. A drawback to this design is that users may have a tendency to “dig” at the froth, rather than maintain a consistent immersion depth, which will decrease precision of this technique for repeat tests performed by the same individual and especially between technicians. Figure 4-1 shows the paddle and scraper dimensions for the equipment tested, offering a comparison of relative size and also allowing for reproduction of the equipment if necessary. The paddles can also be seen in a photograph of the experimental equipment in Figure 3-8 and in Figure 4-2.

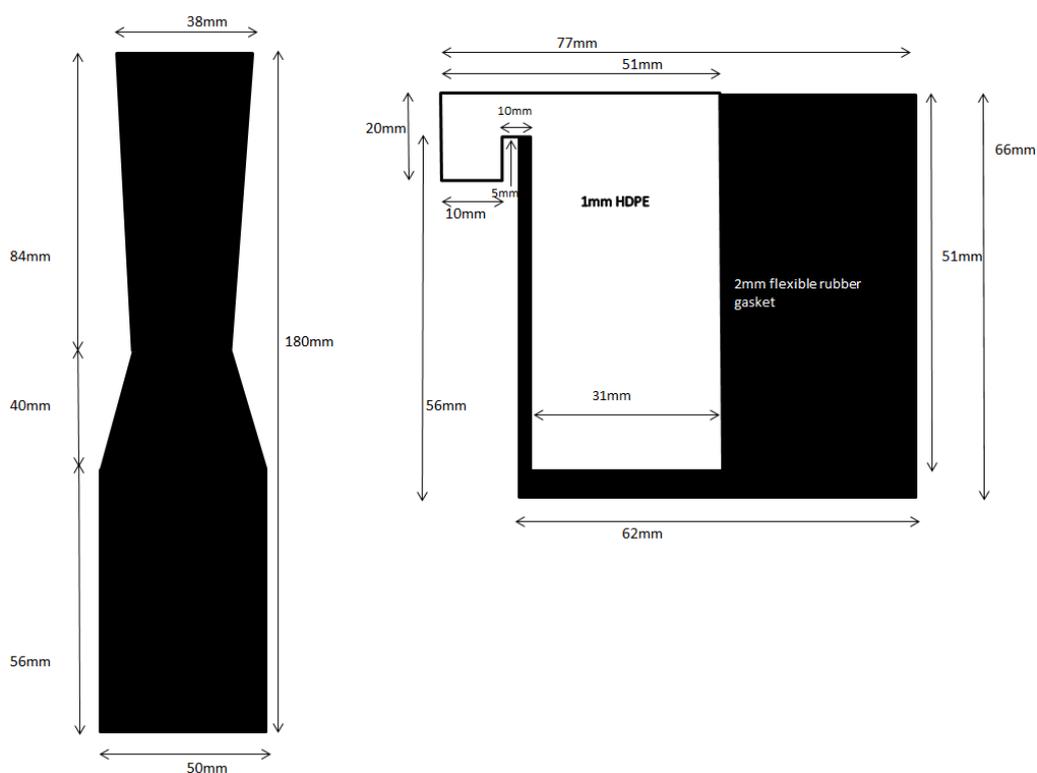


Figure 4-1. Design templates for paddle and scraper used in free gold flash flotation testing



Figure 4-2. Custom scrapers used in free gold flash flotation testing

The paddles are fashioned from stiff, 1 mm HDPE and flexible rubber gasket material. The custom design allowed the rubber to flex around the impeller shaft and along the flotation vessel lip. When this type of paddle is used in a square flotation cell the entire froth surface is scraped in a single pass, at a consistent immersion depth into the froth, thereby increasing repeatability even between different users. Connolly and Dobby (2010) and Runge (2010) confirm the use of custom scrapers increases repeatability by assuring that froth is scraped at a consistent depth regardless of individual operator style when compared to the normal scraper technique, eliminating the need for further testwork within the scope of this project.

Continuous vs. Non-Continuous Operation

Continuous operation requires constant scraping of the froth without stopping during changeover of the concentrate sample collection tray. While the benefit of this method is that there is no additional conditioning time there is also no opportunity to rinse scraper/paddles, vessel and impeller shaft between collections to flush material back into the slurry or replenish water lost to sample collection which maintains a relative bed volume. An additional benefit of this method is that the scraping rate of the froth is consistent.

Non-continuous operation involves scraping the froth at set intervals (every 5 seconds in this testwork) followed by a brief suspension in airflow to change over concentrate sample collection trays, as well as rinse the scraper/paddles, vessel and

impeller shaft. Following the sampling period, the airflow and timer are started again as quickly as possible and froth collection resumes as scheduled. On average only 10 seconds passed during the period where concentrate pans are exchanged which was not deemed significant in comparison to the overall time lapsed during the experiments. Pulp level was roughly maintained by tap water addition from rinsing the vessel and impeller shaft between samples, while the paddles were rinsed into the concentrate trays at the end of the sampling period. The pulp level was variable, depending on agitation, airflow and reagent addition, but it was estimated by noting the region of contact between the agitated pulp and the fixed depth of the immersed paddles to maintain the pulp level. Although, the non-continuous method added conditioning time at regular intervals, it appeared to yield more repeatable data, as is demonstrated in Figure 4-3. In this data set, the paddle scraper design was used to test scraping method while all other variables were held constant.

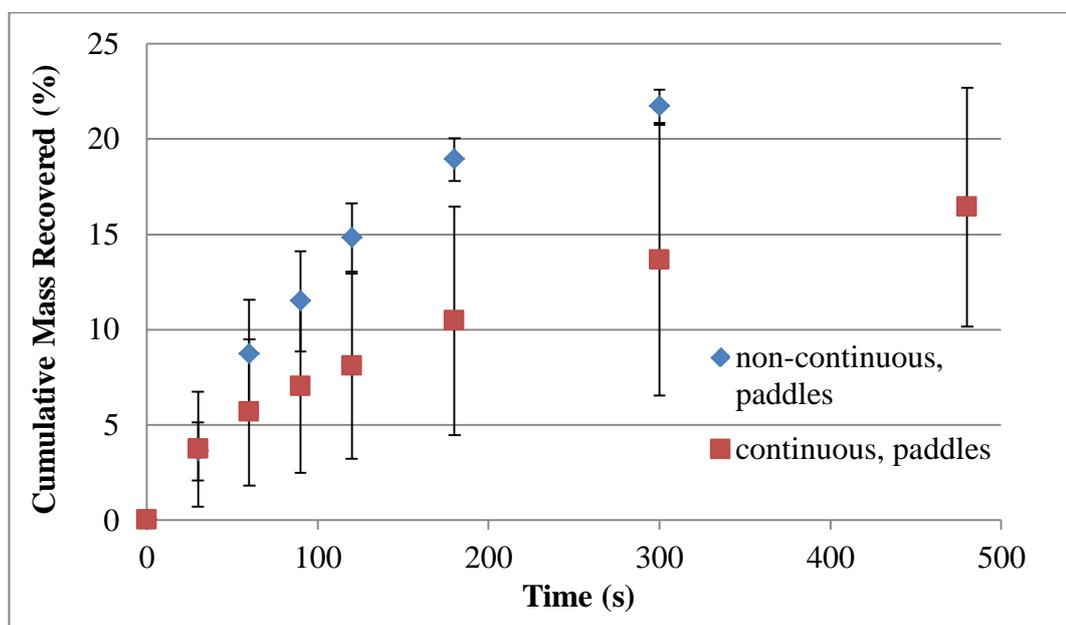


Figure 4-3. A comparison of continuous and timed sample modes of operation

As the figure demonstrates, the variability (given as plus and minus one standard deviation on the average of three tests) is greater for the continuous series as opposed to the more precise mass recovery achieved with the timed sample

operation. One reason for this may be that the number of froth scrapings is fixed with timed sample operation. Inherently due to the nature of the continuous technique, the number of times the froth was scraped is unknown for those tests. The large calculated standard deviation in this method is attributed to the inconsistency of using paddles to scrape froth without a fixed depth of immersion. The non-continuous method is often regarded as the standard method for metallurgical laboratories conducting green-field (fresh ore) testwork and is used in all laboratory flotation testing in this research.

4.2.2 Optimisation of Reagent Concentrations and Operating Conditions

The testwork presented in this chapter was designed to meet the DOE (design of experiments) and RSM (response surface method) statistical approaches using a two level factorial design to reveal interactions which would likely go unnoticed in an OFAT (one factor at a time) design (Anderson and Whitcomb, 2000). This type of experimental design is robust and efficient, and allows for maximum information to be obtained from the fewest number of experiments (Anderson and Whitcomb, 2005). A quarter factorial design, in this case 23 experiments, yields mid-level resolution sufficient for determining independent factors and suggesting interactions between factors. An experimental design software package, Design-Expert 8 (2009) was used to analyse the effect of the tested variables on the response of FRFG in the synthetic ores. To determine the significance of the tested variables, the experimental data was analysed using the analysis of variance (ANOVA) method. Within this model, a p-value is used as a measure of significance; $p < 0.05$ is statistically significant, $0.05 < p < 0.10$ is significant based on the subject matter and $p > 0.10$ means the model is in significant.

In an industrial situation, flash flotation receives feed from the recirculating load of the milling circuit, meaning there are multiple attempts to recover the gold contained in the feed stream. Therefore, it is necessary to characterise the ultimate FRFG content of the ore by increasing the residence time to achieve the ultimate recovery as opposed to just the flash flotation period recovery. In this testwork, concentrate samples were collected at 30, 60, 90, 120, 180, 300 and 480 seconds, as

well as a tails sample. While the Free Gold Flash Flotation test collects concentrate samples over eight minutes for total FRFG content, evaluating recoveries in the first one to two minutes gives an indication of the expected performance in an industrial flash flotation cell. The cumulative gold recoveries for all 23 experiments are given in Figure 4-4 where a wide spread in overall recoveries achieved during the optimisation testwork is evident.

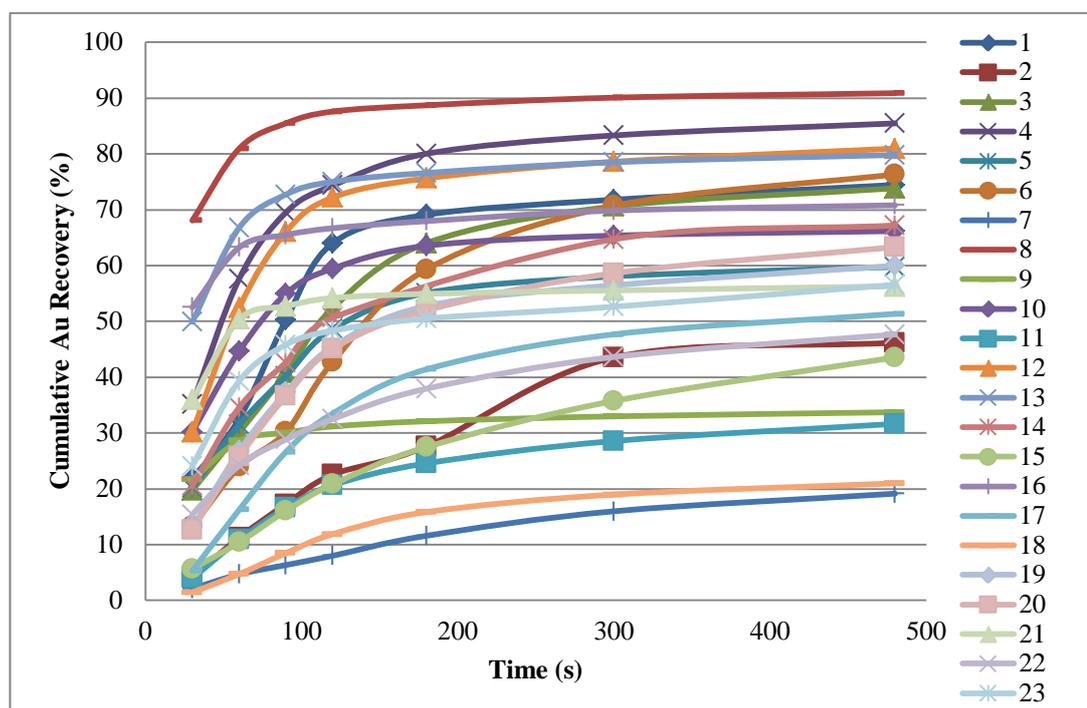


Figure 4-4. Overall gold recoveries in optimisation testwork

Although the data in Figure 4-4 show a large difference in final cumulative recoveries, it is interesting to note the similar trend in response of FRFG recovery in the first two minutes of the testwork, during the flash flotation period, irrespective of the experimental conditions. These data suggest the GRG particles contained in the slurry had kinetics sufficiently favourable for flash flotation applications.

Comparison of Kinetic Models

Kinetic rates using recovery values from this data set (summarised in Table

4-1) have been determined by the following three methods (as described in section 3.3.1):

1. Two component (simplified first order reaction rate),
2. Three component with fixed ratio between k_f and k_s (where $k_f = 2k_s$), and
3. Three component (modified Kelsall).

Table 4-1. Comparison of kinetic rate determination methods (units for k in min^{-1})

ID	2 Component					3 Component (fixed)							3 Component						
	k_f	α_θ	γ_f	MAPE	AIC	k_f	k_s	α_θ	β_s	γ_f	MAPE	AIC	k_f	k_s	α_θ	β_s	γ_f	MAPE	AIC
1	0.72	0.24	0.76	5.99		0.72	0.36	0.24	0.00	0.76	5.99		0.72	0.72	0.24	0.49	0.27	5.99	
2	0.25	0.44	0.56	12.82		1.25	0.25	0.44	0.56	0.00	12.82		0.82	0.25	0.44	0.56	0.00	12.82	
3	0.56	0.24	0.76	4.00		0.56	0.11	0.24	0.00	0.76	4.00		0.56	0.56	0.24	0.46	0.29	4.00	
4	1.12	0.16	0.84	1.50		1.21	0.24	0.14	0.07	0.79	1.33		1.19	0.10	0.11	0.08	0.81	1.27	
5	0.78	0.40	0.60	2.23		0.78	0.16	0.40	0.00	0.60	2.23		0.78	0.46	0.40	0.00	0.60	2.23	
6	0.36	0.17	0.83	5.07		1.80	0.36	0.17	0.83	0.00	5.07		0.36	0.36	0.17	0.62	0.21	5.07	
7	0.22	0.77	0.23	4.25		1.10	0.22	0.77	0.23	0.00	4.25		0.97	0.22	0.77	0.23	0.00	4.25	
8	2.78	0.11	0.89	1.70		3.67	0.73	0.09	0.15	0.75	0.33		3.65	0.74	0.09	0.15	0.75	0.33	
9	2.11	0.68	0.32	2.12		2.74	0.55	0.66	0.06	0.27	0.77		2.55	0.25	0.66	0.05	0.29	0.46	
10	1.18	0.34	0.66	1.01		1.18	0.24	0.34	0.01	0.65	1.00		1.26	0.51	0.34	0.05	0.61	0.85	
11	0.45	0.67	0.33	12.61		0.45	0.09	0.67	0.00	0.33	12.61		0.88	0.45	0.67	0.33	0.00	12.61	
12	1.06	0.20	0.80	2.73		1.06	0.21	0.20	0.00	0.80	2.73		1.06	0.55	0.20	0.00	0.80	2.73	
13	1.99	0.22	0.78	1.48		2.34	0.47	0.20	0.10	0.69	0.32		2.26	0.24	0.19	0.09	0.72	0.12	
14	0.70	0.35	0.65	4.71		1.31	0.26	0.28	0.37	0.35	3.44		1.32	0.27	0.28	0.37	0.35	3.43	
15	0.26	0.50	0.50	3.32		1.30	0.26	0.50	0.50	0.00	3.32		0.82	0.26	0.50	0.50	0.00	3.32	
16	2.81	0.32	0.68	2.07		3.74	0.75	0.30	0.13	0.57	0.62		3.40	0.29	0.28	0.09	0.63	0.18	
17	0.43	0.46	0.54	18.88		0.43	0.09	0.46	0.00	0.54	18.88		0.82	0.43	0.46	0.54	0.00	18.88	
18	0.32	0.76	0.24	27.96	-33.00	1.58	0.32	0.76	0.24	0.00	27.96	-33.00	0.97	0.32	0.76	0.24	0.00	27.96	-33.00
19	0.62	0.39	0.61	5.95		0.62	0.12	0.39	0.00	0.61	5.95		0.62	0.62	0.39	0.37	0.23	5.95	
20	0.55	0.36	0.64	5.29		0.55	0.11	0.36	0.00	0.64	5.29		0.55	0.55	0.36	0.41	0.23	5.29	
21	2.15	0.44	0.56	1.25	-68.13	2.23	0.45	0.44	0.02	0.54	1.14	-69.52	2.22	0.10	0.43	0.02	0.55	1.04	-70.80
22	0.67	0.54	0.46	5.43		1.71	0.34	0.51	0.32	0.18	0.90		1.59	0.28	0.49	0.30	0.21	0.71	
23	1.23	0.46	0.54	2.79		1.49	0.30	0.44	0.10	0.46	2.58		1.45	0.06	0.32	0.19	0.49	2.27	

An assessment of the model's fit to the data for individual experiments can be made by comparing mean absolute percentage errors (MAPE). A higher MAPE value indicates a poor fit to the model where a lower value is indicative of a better fit. Akaike Information Criterion (AIC) values are presented for a high and low MAPE value in this data set. When the MAPE value is high the AIC values are the same, demonstrating any of the three kinetic models can be used fit the data. When the MAPE value is low there is a larger deviation in the AIC values between the three models with the three component model having the lowest AIC value. The minimised AIC value calculated for the three component model establishes that it is the best fit for the kinetic data in this testwork considering many of the experiments

exhibit low MAPE values.

Silver Content in the BCC concentrate

The literature review presented in Chapter 2 suggested that the silver content of native gold can preferentially influence the floatability of the particles. Previous AAS assays demonstrate the BCC concentrate used as the source of gold in the synthetic ore has 9:1 ratio of gold to silver although SEM has revealed that individual particles vary greatly in the ratio and the patterns of distribution for silver in the gold particles (See Appendix 9.3). The ratios of gold recovery to silver recovery for each sample point (concentrates and tails) in the data set are tabulated in Table 4-2 and shown in Figure 4-5.

Table 4-2. Table of gold to silver ratios in the optimisation testwork

Cumulative time (s)	Experiment ID																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
30	2.1	1.4	9.1	1.3	2.8	1.2	0.9	2.3	2.7	1.8	3.6	1.8	3.4	1.9	1.4	3.7	3.5	3.5	2.6	1.7	4.4	1.7	1.6
60	3.6	1.5	1.4	3.1	2.9	1.4	1.0	2.8	2.7	2.3	3.7	2.5	3.8	2.2	1.5	3.9	3.9	3.7	2.8	2.8	4.2	2.2	2.5
90	3.9	1.6	1.9	3.2	3.0	1.5	1.1	2.9	2.3	2.7	3.6	3.1	3.6	2.3	1.6	3.1	4.1	3.6	3.2	3.7	2.9	3.0	3.0
120	3.8	1.7	2.6	3.1	3.3	2.3	1.2	2.9	2.5	2.5	3.5	3.1	3.3	2.8	1.9	2.9	4.4	3.9	3.5	4.1	3.3	3.2	3.2
180	2.3	2.0	2.9	2.9	3.3	2.5	1.1	2.2	2.1	2.6	3.5	2.8	3.0	2.8	2.1	2.9	4.3	4.2	3.6	4.4	2.8	3.9	3.3
300	4.2	3.1	2.8	2.8	2.9	2.6	1.0	2.6	2.4	2.4	3.6	3.0	3.4	2.8	2.5	3.0	4.5	4.5	3.2	4.5	2.9	4.3	3.5
480	4.2	2.7	2.8	2.7	2.9	2.5	1.2	2.3	2.7	2.2	3.9	3.3	2.8	2.6	3.5	2.6	4.5	4.2	3.6	4.6	3.8	4.5	4.0
tails	5.2	2.1	2.8	3.1	3.3	2.4	2.7	2.9	3.2	4.1	4.0	3.4	3.8	3.5	4.2	4.2	4.9	4.6	4.6	4.2	4.7	4.6	3.5

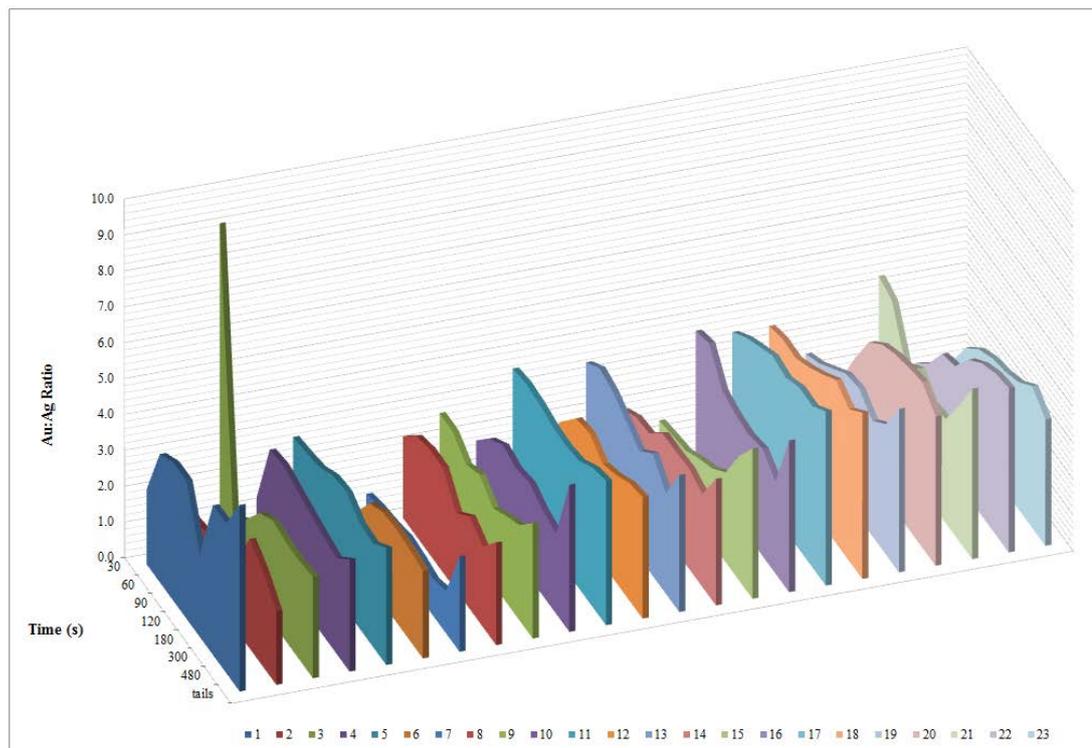


Figure 4-5. Gold to silver ratios in the optimisation testwork

These data show a trend of an increasing proportion of gold in the tails compared to silver which is in agreement with the literature published on electrom flotation.

Ultimate Recoveries and Optimisation Testwork Summary

In addition to the recoveries of gold and silver, sulfur and overall mass pull to the concentrate were also measured. A matrix showing test conditions and ultimate recovery results for this round of optimisation testing is given in Table 4-3. (Note: Firstly, “Sulfide Addition” is the per cent of sulfur as a result of the addition of the pyrite to the synthetic ore, while the “Sulfur” column refers to a calculated recovery based on a LECO assay value of elemental sulfur. Secondly, the feed grade was back calculated based on concentrate and tails assays.)

Table 4-3. Optimisation testwork matrix

EXP ID	Factors						Responses			
	Air Flow	Agitation	Collector	Frother	Sulfide	Activator	Au	Ag	S	Mass
	LPM	RPM	PAX g/t	MIBC g/t	Addition %	CuSO ₄ *5H ₂ O g/t	Recovery %	Recovery %	Recovery %	Pull %
1	10	1200	25	10	5	0	74	84	96	12
2	10	1000	10	20	0	20	47	36	63	3
3	5	1000	25	20	5	0	74	75	95	12
4	10	1000	25	10	0	0	84	90	76	6
5	5	1200	10	20	0	20	60	62	2	4
6	5	1200	25	20	5	20	76	81	97	11
7	10	1000	10	10	5	20	19	37	87	9
8	10	1200	25	20	0	0	91	92	94	7
9	5	1000	10	20	0	0	34	38	2	5
10	10	1200	10	20	5	20	66	79	99	12
11	10	1000	10	10	0	20	32	34	39	1
12	5	1200	10	20	5	0	81	86	98	11
13	5	1200	25	10	0	0	80	81	63	7
14	5	1200	10	10	5	20	67	76	100	10
15	5	1000	10	10	5	0	44	62	96	10
16	10	1200	10	10	0	0	71	74	39	6
17	10	1000	25	20	0	20	51	55	82	2
18	10	1200	25	10	0	20	21	24	88	1
19	10	1000	10	20	5	0	60	69	95	13
20	10	1000	25	20	5	20	63	71	99	12
21	10	1200	25	10	0	0	56	60	100	7
22	5	1000	25	10	5	20	48	63	98	11
23	10	1200	25	20	5	20	57	68	98	13

Mass Pull to Concentrate

Review of the response data in Table 4-3 makes evident a connection between mass pull and sulfur addition. Figure 4-6 demonstrates that the relationship of mass pull into the concentrate is sensitive to the presence of sulfides, as shown in the testwork with sulfide additions. However, subsequent multi variable analysis of the data set shows no direct correlation of increased mass pull to increased gold recovery. The increase in recovery is due to the interaction between several tested variables resulting in higher measured responses of gold recovery and mass pull, as further discussed later in this section. Teague et al. (1999a) had suggested that free gold recovery can be tied to mass pull and the recovery of gangue material, though the data presented in Figure 4-6 do not directly support this statement.

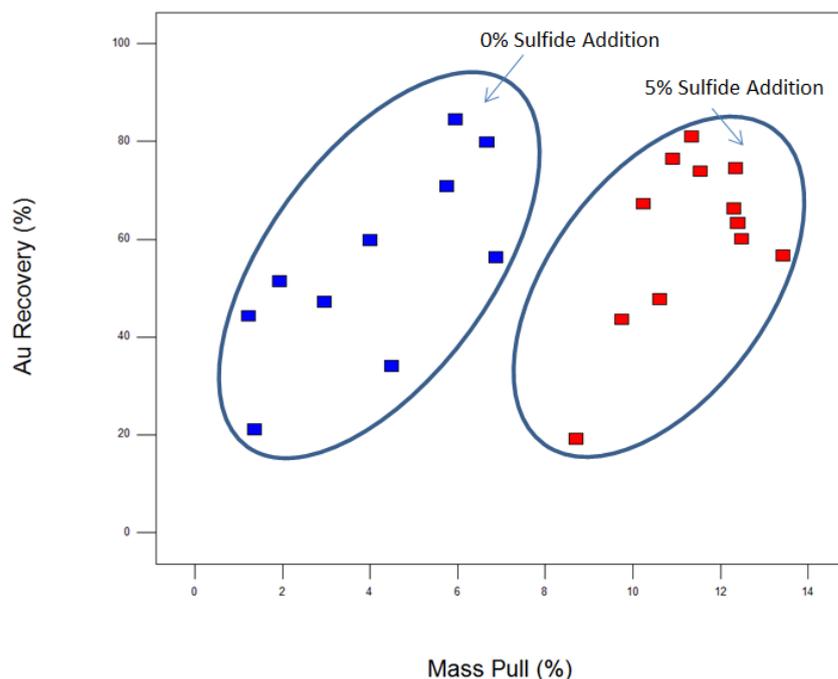


Figure 4-6. The relationship of mass pull and gold recovery as a function of sulfide presence in laboratory flash flotation testing

In contrast, the two highest recoveries of gold (91 and 84%) are actually found in the lower mass pull region. One explanation is that it is possible that the sulfide “crowds out” the free gold, as shown by the slower kinetic rates and reduced recoveries. The crowding out mechanism has also been speculated by other researchers (Dunne, 2005; Teague et al., 1999a). It has been shown that sulfide bubble loading will decrease the hydrophobic bubble attachment of free gold and in these cases, true flotation of free gold is inhibited by high sulfide loading. Therefore, it may be that free gold entrainment is the mechanism responsible for gold recovery (Marsden and House, 2006). Considering that the contribution of a valuable material to the concentrate made by entrainment is only a significant factor when the feed grade is high (which is not the case for free gold in this instance), the effect of entrainment is negligible and will not be further deliberated in this study. More likely, it is possible that the poor recovery of free gold during flotation in the presence of sulfides may be attributed to unfavourable changes in pulp chemistry or competitive collector adsorption. Ultimately, the overall effect on free gold recovery

of sulfide present in the ore at the levels is statistically insignificant, given the resolution of this factorial design.

The Influence of Collector

When the collector PAX was evaluated as an independent factor, it appeared to promote the recovery of free gold, regardless of sulfide addition. The higher level of the collector PAX (25 g/t) was common to six of the top seven gold recoveries, as seen in Figure 4-7.

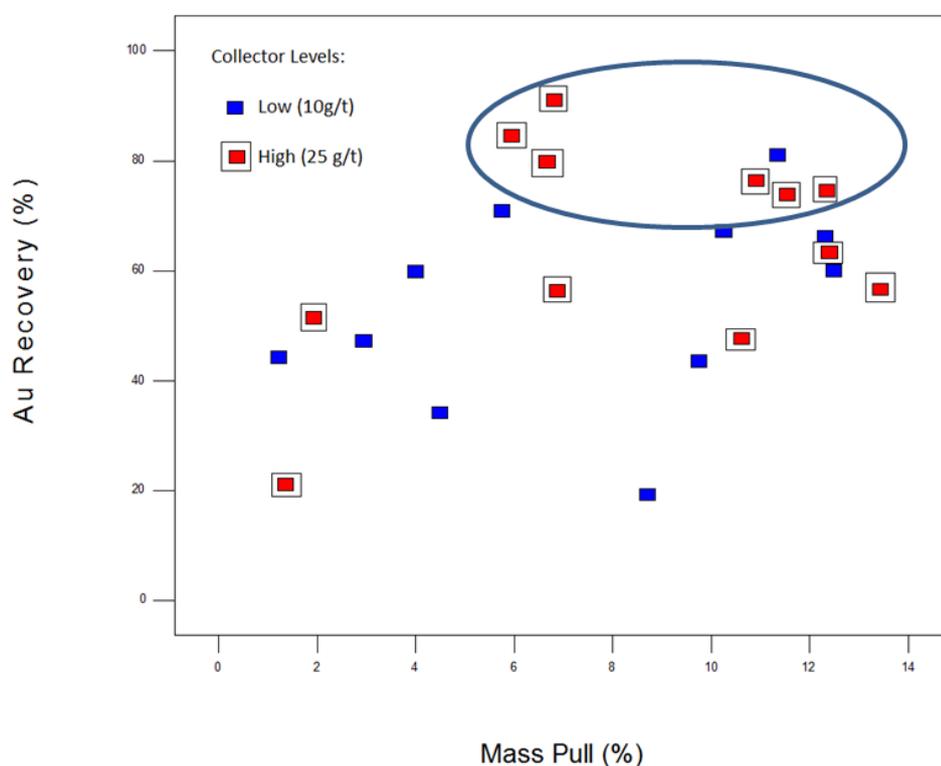


Figure 4-7. Impact of collector levels on gold recovery and mass pull

The Effect of Agitation

Coarse free gold requires adequate agitation to maintain its suspension within the pulp. Lins and Adamain (1993) found rising eddies within a laboratory flotation cell provide enough energy to lift bubble-coarse gold aggregates into the froth. Researchers have also suggested too much agitation can result in smaller bubbles

which are less able to carry the dense gold to the surface and will contribute to froth instability (Yoon, 2000). If there is too much turbulence at the surface due to high agitator speeds, coarse particles are more likely to detach at the pulp-froth interface (Seaman et al., 2006). In this study, at high (1200 RPM) agitation, when the collector dosage is increased to 25 g/t PAX, the trend of decreased GRG recovery was noticed. Figure 4-8 shows optimal gold recovery, identified in the white boxes, was actually achieved in with the combination of lower collector dosage and increased agitation. This suggests the bubbles produced at this agitation level were not yet too fine nor was turbulence at the surface too great to recover the gold. It may be possible other factors are having an influence on recovery, such as bubble crowding by the sulfides at the higher PAX addition.

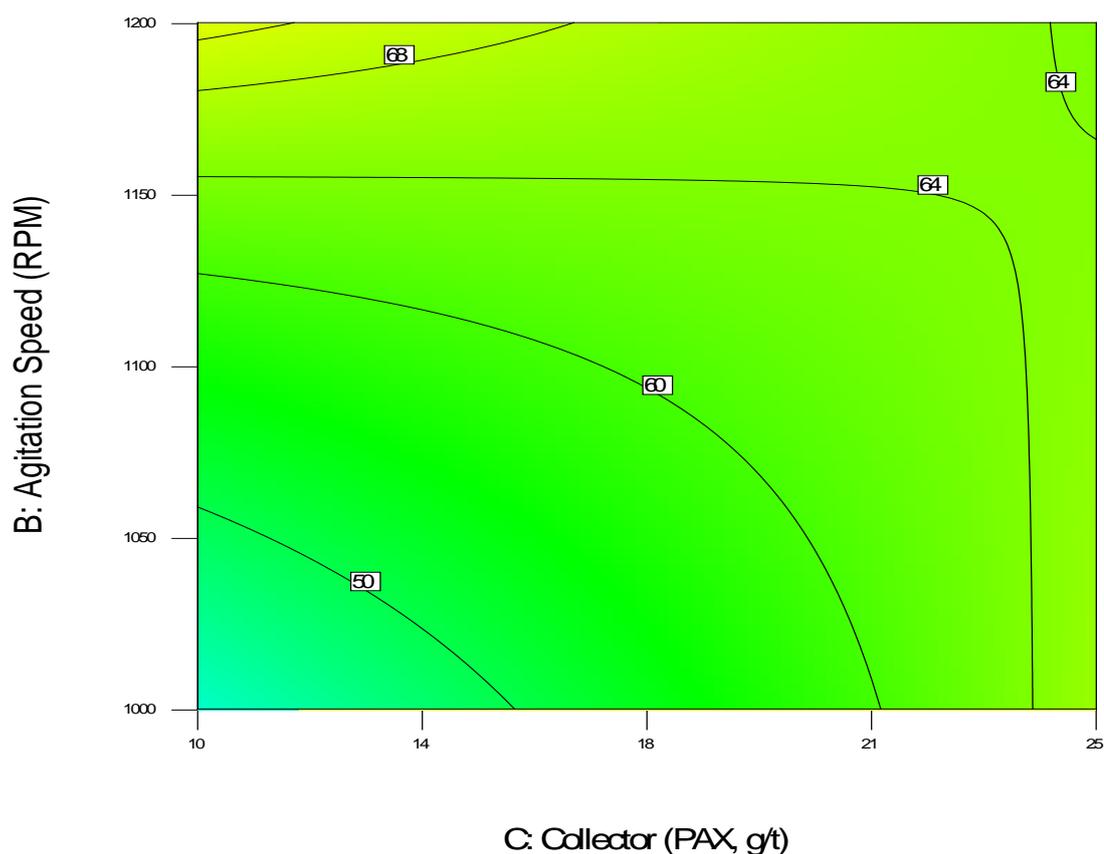


Figure 4-8. The combined effect of agitation and collector on gold recovery

Copper Sulfate as a Free Gold Activator

The use of copper sulfate as an activator in sulfide and free gold flotation has been noted at several plants. Teague, et al. (1999a) found enhanced recovery of free gold when copper sulfate is added after PAX in the circuit, which was the order of addition in this research. It has been suggested that copper sulfate activates iron and, in turn, floats iron-gold complexes created during grinding. However, copper is less noble than gold and so it would not be expected to directly activate gold (Monte et al., 2002). Although some operators recommend the use of copper sulfate to optimise froth stability, a proven mechanism for activation of free gold by copper has yet to be established (Dunne, 2005). The average gold recoveries, with and without the addition of copper sulfate, are presented in Figure 4-9. Given that there is no overlap in the bounds marked by the standard deviations; these data do not support the use of copper sulfate additions after PAX to increase free gold recovery, regardless of the presence or absence of sulfides.

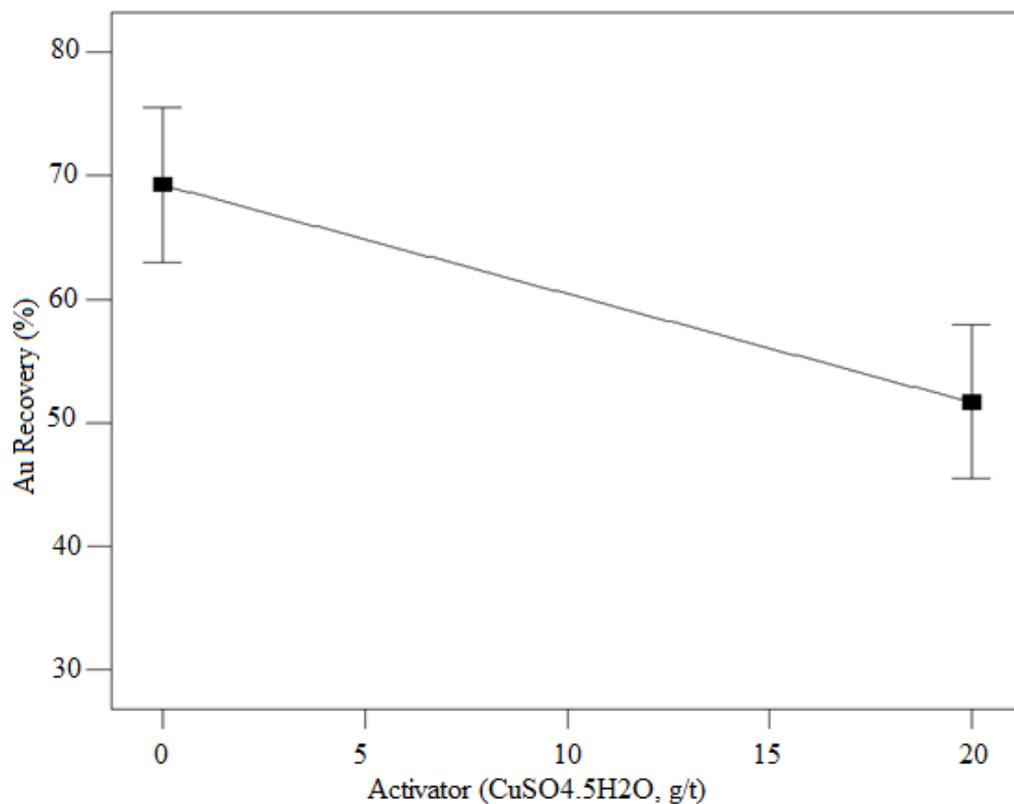


Figure 4-9. The influence of copper sulfate as an activator for free gold recovery

Significant Factors

The results reported in this section have identified the interaction of agitation, collector and activator, within the tested levels, as having the most significant impact upon FRFG recovery in the laboratory scale flash flotation testwork. Figure 4-10 reveals the best recovery is achieved in the upper left and lower right of the cube, because statistically there is little difference in the values when the standard deviation for gold recovery using the Free Gold Flash Flotation test is +/-4.63% (average).

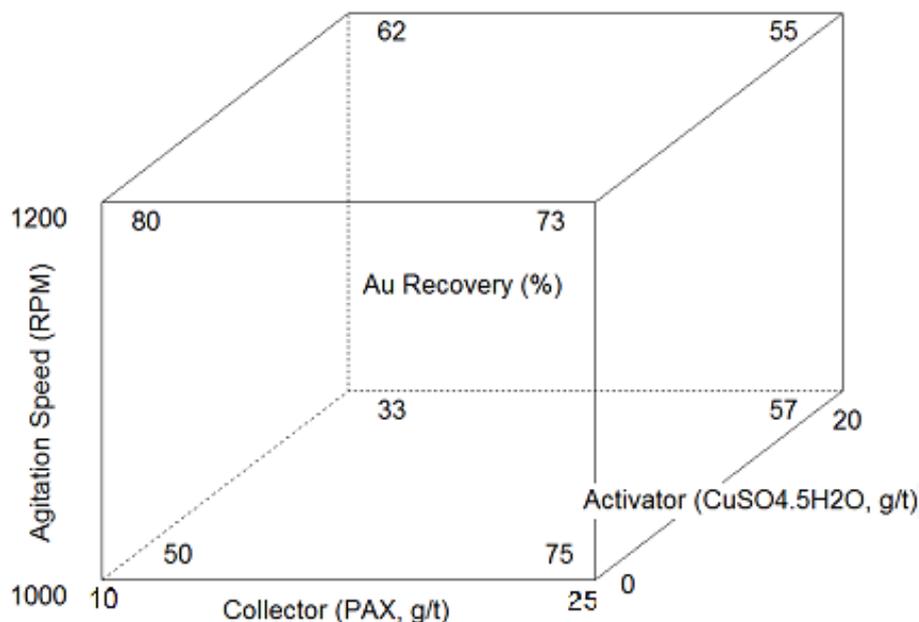


Figure 4-10. Significant factors in the recovery of free gold

The amount of MIBC added and the airflow rate at tested levels were deemed to be insignificant variables by analysis of experimental recovery data. This implies that these factors were sufficient to recover free gold in laboratory conditions at both levels tested (i.e. MIBC addition = 10 or 20 g/t and airflow rate = 1000 or 1200 LPM), having neither a positive nor a negative impact on free gold floatability. Future studies using this procedure will operate at the midpoints of the tested ranges for airflow and frother midpoints to minimise any unintended impact upon free gold recovery (Section 4.2.4.).

Although the recovery of gold and silver and the role of mass pull have been the focus of this section, the recovery of sulfur was also measured. In the case of zero sulfur addition, the recovery of sulfur was clouded by background noise and the limits of the LECO analytical detection limits. While a correlation between increased sulfide content and increased mass pull was established, due to analytical limitations, the influence of sulfide presence on free gold recovery was unable to be resolved in this testwork.

4.2.3 Surface Refreshment

In addition to assessing the effect of operational/mechanical parameters and reagent additions, the effect of surface refreshment was evaluated with regards to the recovery of FRFG via the Free Gold Laboratory Flotation test. These tests aimed to determine if improved recoveries could be achieved by refreshing the surface of free gold or if gangue material would act to coat the gold and decrease floatability and if storage and sample preparation requirements for free gold flash flotation testwork would be similar to the strict requirements of sulfide flotation testwork. Surface refreshment was conducted by dry bottle rolling the flotation feed material for a specified time, immediately prior to flash flotation testing. No reagents or grinding media were used in the surface refreshment grind. Figure 4-11 makes apparent slight differences in recovery but the relevant time data points had overlapping standard deviations.

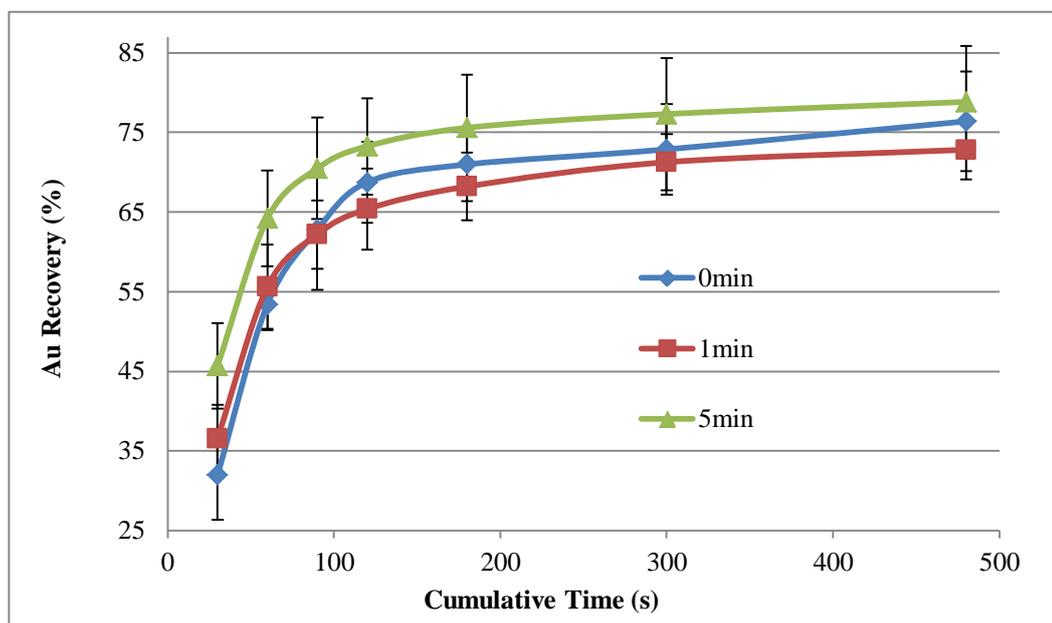


Figure 4-11. The effect of surface refreshment on the recovery of free gold

Figure 4-11 suggests the effect of dry surface refreshment on the synthetic ores, at the intervals tested, was negligible. The graph indicates there might have been an increased kinetic response with 5 minutes of dry refreshing, which could

prove important in flash flotation period recoveries though not for ultimate FRFG content as the test is designed to characterise. Since surface refreshment was not proven to be deleterious, a five minute dry grind should be performed on dry ore samples from milling circuits immediately prior to the Free Gold Flash Flotation Test, as described in the in the standard operating procedure (SOP) in the next section (and in Appendix 9.1.).

4.2.4 The Free Gold Flash Flotation Recovery Test and Intensive Cyanidation Standard Operating Procedures

The results from reagent and operational parameter testwork performed in this chapter have provided a standard set of operating conditions to be used in the Free Gold Flash Flotation test to characterise the ultimate FRFG content of an ore. Although operation at the stated levels for included factors will not always yield the greatest free gold recovery, these combinations of factors will result in statistically sound data. That is to say, recoveries achieved at the conditions listed in Table 4-4 will minimise standard deviation and the deviation that is present is known and can be accounted for with this method. The conditions listed are part of the formal SOP available in full detail the Appendix (9.2).

Table 4-4. Free Gold Flash Flotation test operating conditions

<u>Factor</u>	<u>Unit</u>	<u>Level</u>
Air Flow	LPM	7.5
Agitation Speed	RPM	1200
Collector (PAX)	g/t	25, 50
Frother (MIBC)	g/t	15
Activator (CuSO ₄)	g/t	0
Sulfide Addition	%	0
Solids Density	%	45
Surface Refreshment	min	5
Concentrate collection (elapsed time)	sec	30, 60, 90, 120, 180, 300, 480

To determine repeatability, three tests were conducted following the SOP with moderate changes made to reagent and operational variable levels, each test being repeated in triplicate for a total of nine tests. Results shows strict adherence to the methods detailed in the SOP yields acceptable standard deviations as listed in Table 4-5.

Table 4-5. Standard deviations (sd) for mass pull and gold recovery expected when using the Free Gold Flash Flotation test to determine FRFG content

Test #	Mass Pull Variation % (+/- sd)	Average	Gold Recovery Variation % (+/- sd)	Average
1A	0.36	0.47	3.05	4.63
1B	0.51		5.73	
1C	0.47		5.11	

When testing brownfield type ores, it is recommended that a sample be obtained from the same feed stream as the flash flotation unit receives on site (usually the cyclone underflow) and screen at P₁₀₀ 600 µm. The Free Gold Flash Flotation test should then be performed at two collector levels, as indicated, to identify the maximum recovery and determine the FRFG content. To find the FRFG

content in a greenfield type ore, the sample should be crushed and ground to P₁₀₀ 600 µm before commencement of the Free Gold Flash Flotation test.

4.3 Summary

This chapter has detailed the development of the Free Gold Flash Flotation test which serves to characterise the maximum FRFG content of an ore. The test has proven to be robust and repeatable in quantifying the FRFG content of a synthetic ore.

The Free Gold Flash Flotation test has been used to study the effects of reagent addition, operational parameters and surface refreshment on gold and silver recoveries as well as mass pull to the concentrate. Using this method, the FRFG laboratory recoveries demonstrated a repeatability of +/- 0.45% (average) for mass pull while gold recovery was less precise at +/-4.63% (average).

The factors agitation, collector level and sulfide addition demonstrated variable responses when evaluated independently or in combination while aeration rate, surface refreshment, sulfide addition and frother level show no impact on recovery of FRFG in the ranges tested. The use of copper sulfate as an activator appeared deleterious for the recovery of FRFG. Based on these results, the Free Gold Flash Flotation test SOP was developed which can be applied to characterise the FRFG content of an ore.

Prior to the development of the Free Gold Flash Flotation test, there existed no method for determination of FRFG content in ore for either greenfield or brownfield applications. Using the Free Gold Flash Flotation test, additional testwork on collector addition, per size department and gold genesis was then investigated to determine their impact upon FRFG recovery.

CHAPTER 5. EFFECT OF COLLECTOR DOSAGE AND FREE GOLD GENESIS ON PER SIZE RESPONSE

5.1 Introduction and Background

The development of the Free Gold Flash Flotation test (detailed in Chapter 4) has allowed for quantification of FRFG content of any desired ore. The test identified a variable response in recovery of FRFG as a function of PAX concentration. Previously, no studies have been conducted focusing on the effect of collector dosage and free gold origin on per size response, particularly in reference to flash flotation. In this chapter, synthetic ore with two types of gold (BCC concentrate and pure Au powder) was subjected to the Free Gold Flash Flotation test at varying PAX additions. The resulting concentrates were screened into coarse (+212 μm), intermediate (-212/+38 μm) and fine (-38 μm) fractions for kinetic analysis.

The observed influence of particle size and gold genesis is used to explain their impact upon FRFG behaviour or floatability. Floatability is used in this thesis to simply refer to the portion of material that is capable of floating as demonstrated by recovery values. The knowledge gained from this research will contribute to a better understanding of the impact of particle size, milling effects, residence time, alloy effect, natural hydrophobicity and collector addition upon the recovery of FRFG in the milling circuit.

5.2 Results

The recovery of particles in individual size ranges is important because those values demonstrate what proportion of that sized material is recovered under specific conditions; this information will be labelled as fractional recovery. For example, 14 % of coarse gold from the GRG concentrate was recovered without PAX addition, as shown in Figure 5-1, suggesting that 86 % of the gold in the coarse GRG concentrate reported to tails in this test. Combined or total recovery refers to the sum of the recoveries for all size fractions; these types of overall recovery values can be seen for all tests in Sections 5.2.9 and 5.2.10 (in Figure 5-15 and Figure 5-16).

5.2.1 Coarse Gold Recoveries

The floatability of +212 μm gold, illustrated in Figure 5-1, is of interest in this study because these are the particles generally considered to be too large for flotation, with preference given to gravity recovery in this size fraction. For reference, industrial flash flotation usually operates around 10-25 g/t of PAX addition (near the middle range of the PAX levels evaluated in this testwork) with roughly two minutes assumed for residence time. Therefore, the first two minutes (which have been represented by the initial four data points in Figure 5-1 through Figure 5-14, and includes all data presented in Figure 5-16) roughly represent flash flotation, and have been denoted as the flash flotation period.

Figure 5-1 demonstrates that coarse gold recovery and flotation kinetics were improved with the addition of PAX, with the GRG displaying superior recovery compared to the Au powder in tests where PAX was added.

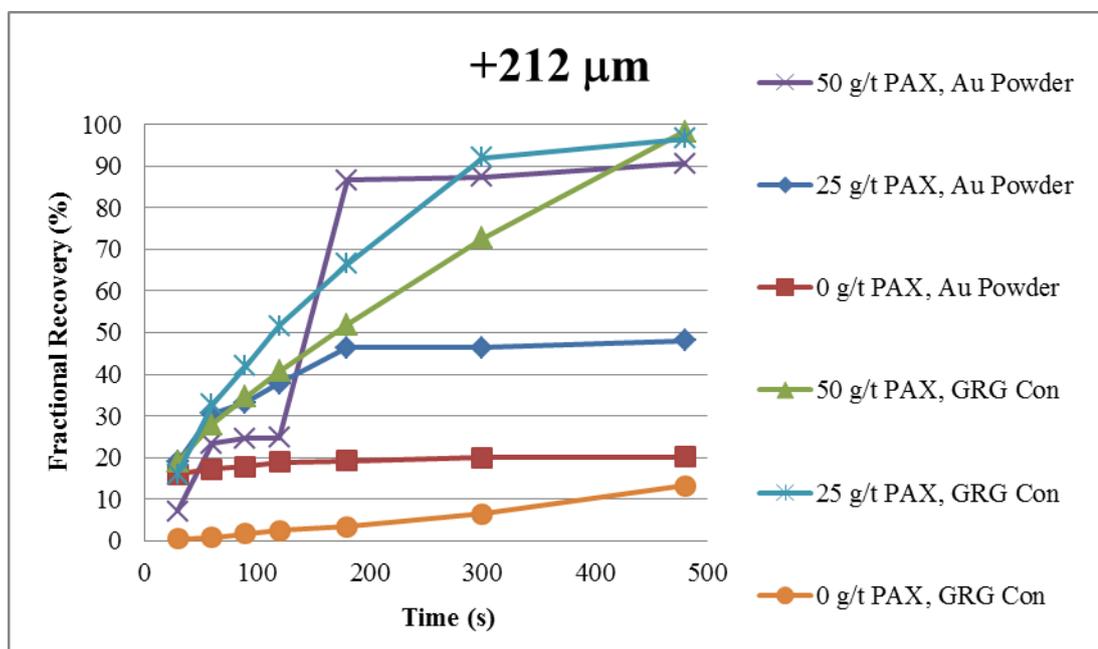


Figure 5-1. Fractional recoveries of +212 μm particles from GRG concentrate and Au powder, with varying levels of PAX addition

Using the Free Gold Flash Flotation Test, ultimately 97 % of the coarse free gold contained in the GRG concentrate was recovered with 25 or 50 g/t PAX addition. The coarse Au powder particles were 90 % recovered with 50 g/t PAX, though only 48 % recovery was achieved when the same particles were floated with 25 g/t PAX. Collectorless flotation was less effective, resulting in recoveries of only 20 % of Au powder and 13 % of free gold from the GRG concentrate in the coarse size range. The nonlinear shape of the +212 Au powder at 50g/t PAX is likely an example of the nugget effect, in this case, where one coarse particle has a pronounced impact on cumulative fractional recovery.

The response of coarse gold particles in the flash flotation period as a function of PAX addition is demonstrated in Figure 5-2.

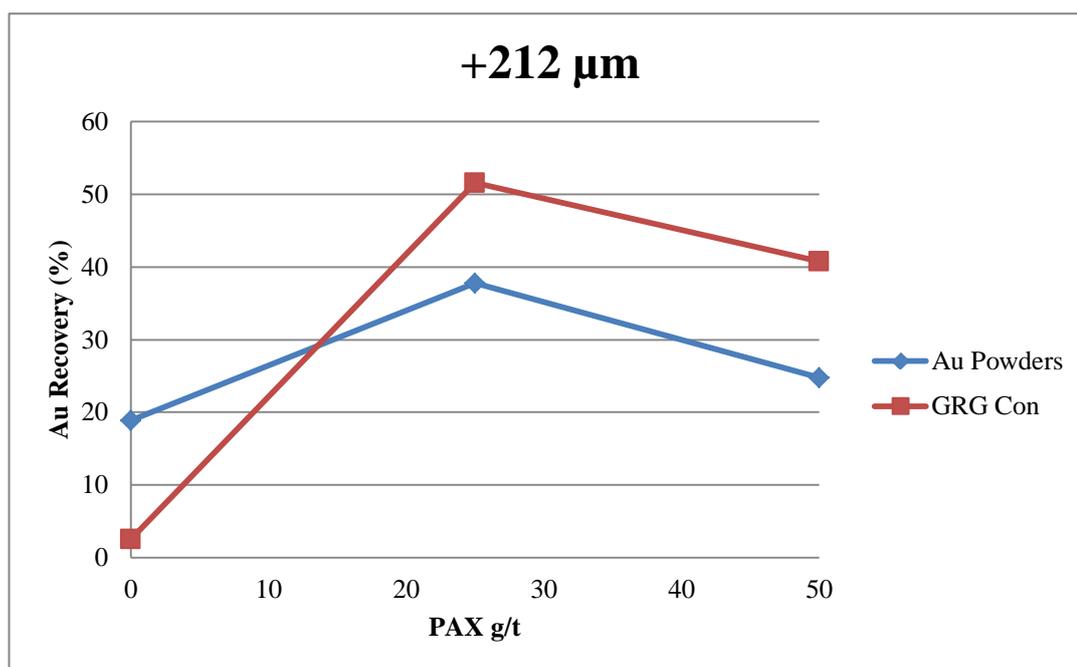


Figure 5-2. Fractional flash flotation period recoveries of +212 μm particles from GRG concentrate and Au powder as a function of PAX addition

Acceptable flash flotation period recoveries of around 50% of the coarse BCC concentrate material was noted at both levels of PAX addition. Based on this

data similar sized FRFG material could be a likely candidate for industrial flash flotation recovery.

5.2.2 Intermediate Gold Recoveries

The -212 +38 μm size range, with gold recoveries given in Figure 5-3, is of particular interest because this is the suggested area of competition between BCCs and flash flotation in parallel operation.

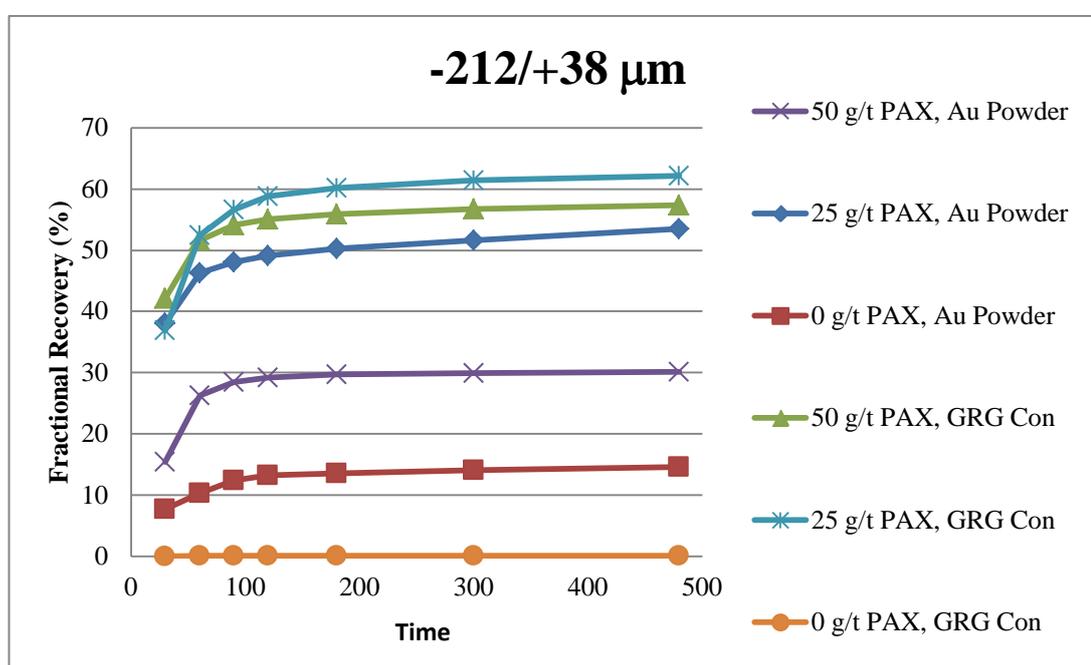


Figure 5-3. Fractional recoveries of -212/+38 μm particles from GRG concentrate and Au powder, with varying levels of PAX addition

Review of these data suggest that a moderate PAX addition improved intermediate particle recovery when compared to tests where no PAX was added, although both the GRG and the Au powder responded slightly better to the lower level of PAX addition. A much lower ultimate recovery was achieved intermediate size fraction of GRG material as compared to the coarse particle GRG (Figure 5-1) in both cases of PAX addition. As with the coarse particle data, the intermediate Au powder particle recovery is lower than comparable GRG recoveries. Collectorless flotation recovered the least amount of intermediate particles in both the Au powder

and GRG concentrate tests, at less than 15 % and less than 1 %, respectively. The flash flotation period recovery as a function of PAX addition is given in Figure 5-4.

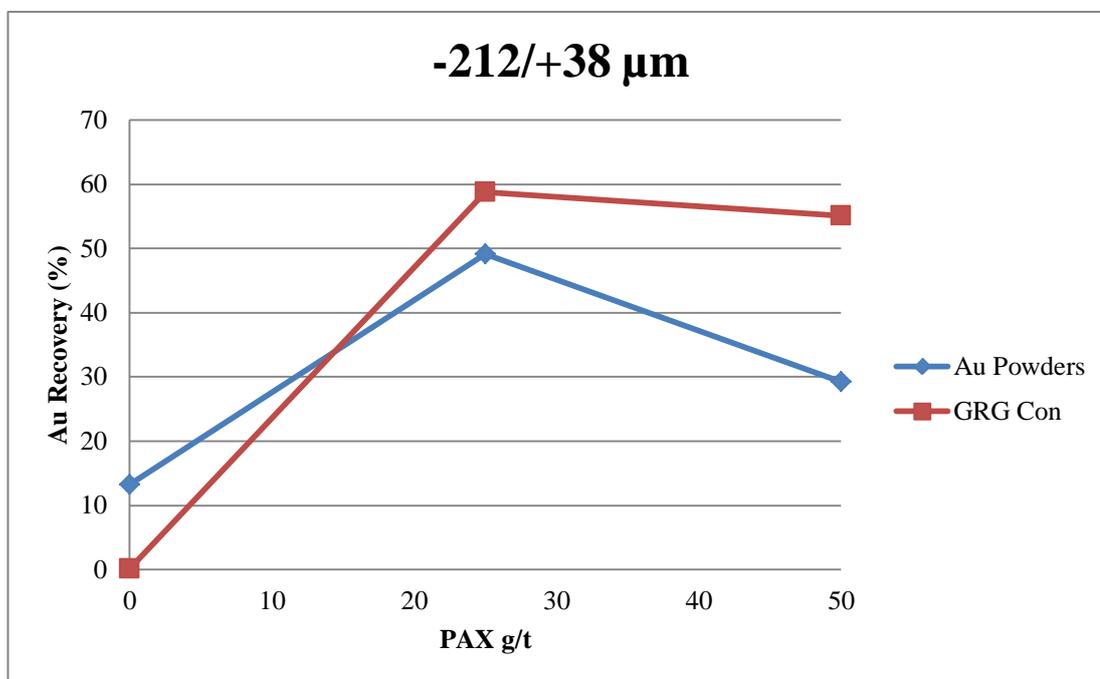


Figure 5-4. Fractional flash flotation flotation period recoveries of -212/+38 μm particles from GRG concentrate and Au powder as a function of PAX addition

As with the coarse data set, there is no significant difference between flash flotation recoveries and ultimate recoveries concerning BCC concentrate particles, suggesting similar sized FRFG material could be a likely candidate for industrial flash flotation recovery.

5.2.3 Fine Particle Recoveries

The fractional recoveries of -38 μm particles are demonstrated in Figure 5-5.

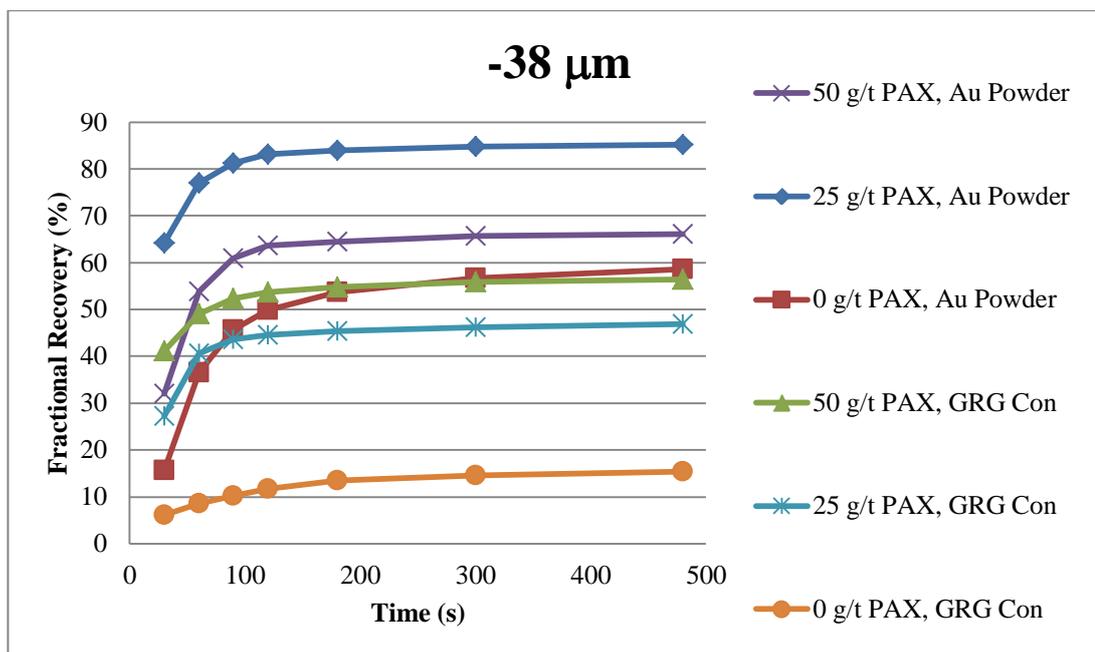


Figure 5-5. Fractional recoveries of -38 μm particles from GRG concentrate and Au powder, with varying levels of PAX addition

This is the size range for which flash flotation has been the unit operation recommended for free gold recovery within the milling circuit. Interestingly, this is the only size range where the Au powder particles were recovered better than the GRG concentrate regardless of PAX addition. Like the intermediate particles, fine Au powder demonstrated the highest ultimate recovery with 25 g/t PAX addition which decreased when PAX was increased to 50 g/t. The collectorless flotation of Au powder recovered the same amount as 50 g/t PAX addition to the GRG concentrate, with respective recoveries of 59 and 57 % not being statistically different. Again the fine GRG particles recovered in collectorless flotation have shown the lowest recovery of PAX levels and of each gold type, just as with the coarse and intermediate size fractions. Flash flotation period recoveries are shown in Figure 5-6.

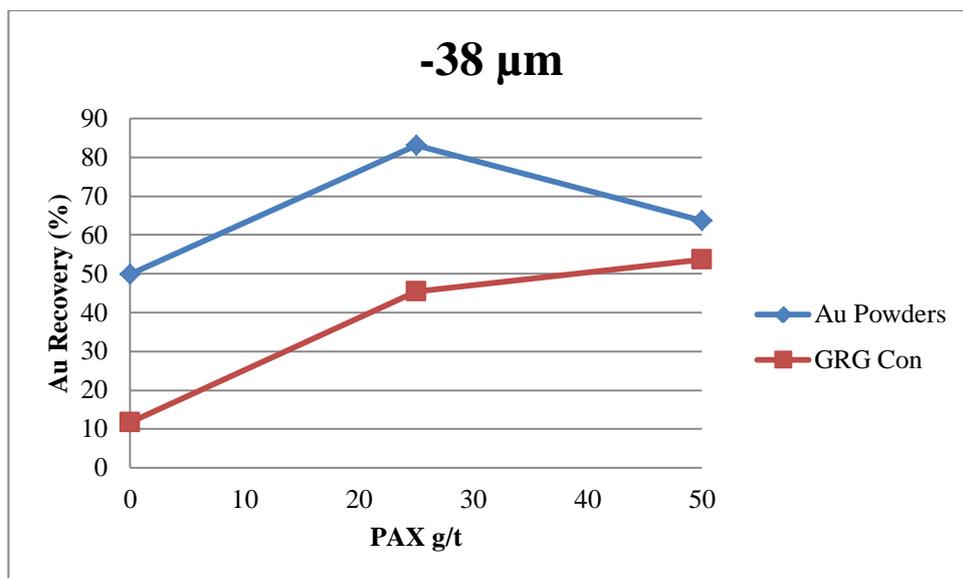


Figure 5-6. Fractional flash flotation period recoveries of -38 μm particles from GRG concentrate and Au powder as a function of PAX addition

While the – 38 μm Au powder particles achieve higher fractional recoveries regardless of PAX addition in comparison to the BCC concentrate gold particles, the fine BCC concentrate gold particles have demonstrated an increase in recovery with PAX addition, which was not the trend for the fine Au powder particles.

5.2.4 Recoveries with High Collector Dosage

Figure 5-7 shows the effect of 50 g/t PAX addition on gold recoveries in all size ranges.

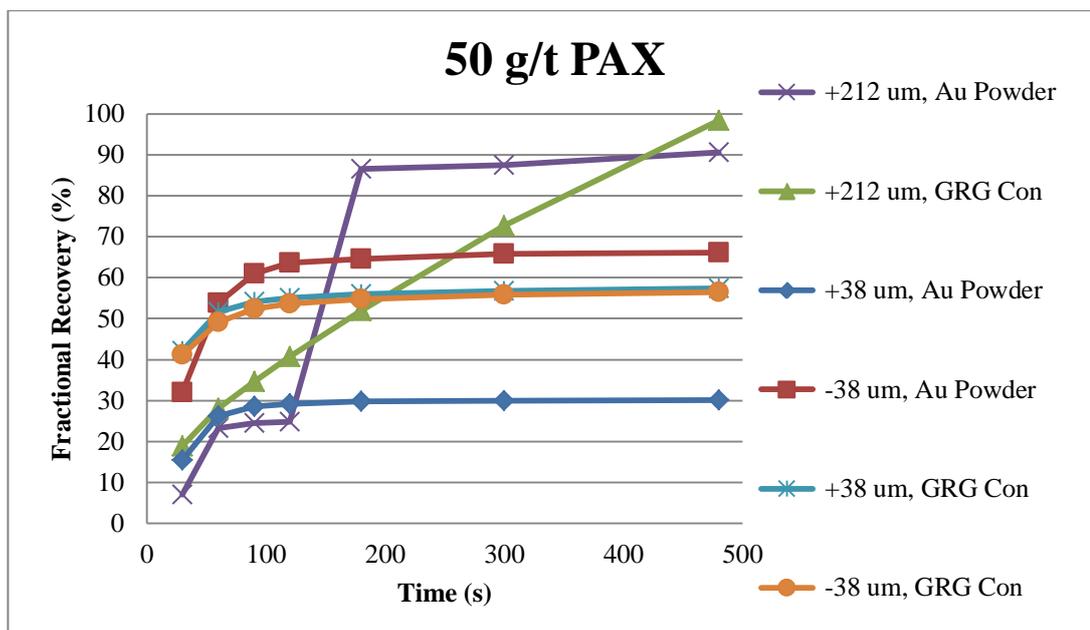


Figure 5-7. Fractional recoveries of particles from GRG concentrate and Au powder at 50 g/t PAX addition

In this testwork the coarse gold particles from both the GRG concentrate and Au powder particles achieved the highest fractional recoveries of all particle sizes and types. While the intermediate and fine GRG particles were recovered identically with 50 g/t PAX the fine Au powder was recovered better than the intermediate Au powder. Flash flotation period recoveries at 50 g/t PAX, shown in Figure 5-8, demonstrate a decreased fractional recovery of the Au powder particles in the coarse and intermediate size fractions in comparison to the fine material. The impact of increasing size appears less severe for the BCC concentrate samples in the data set. Again, the nonlinear shape of the time versus recovery curve for +212 Au powder particles at 50g/t PAX is likely an example of the nugget effect, where one coarse particle has a pronounced impact on cumulative fractional recovery.

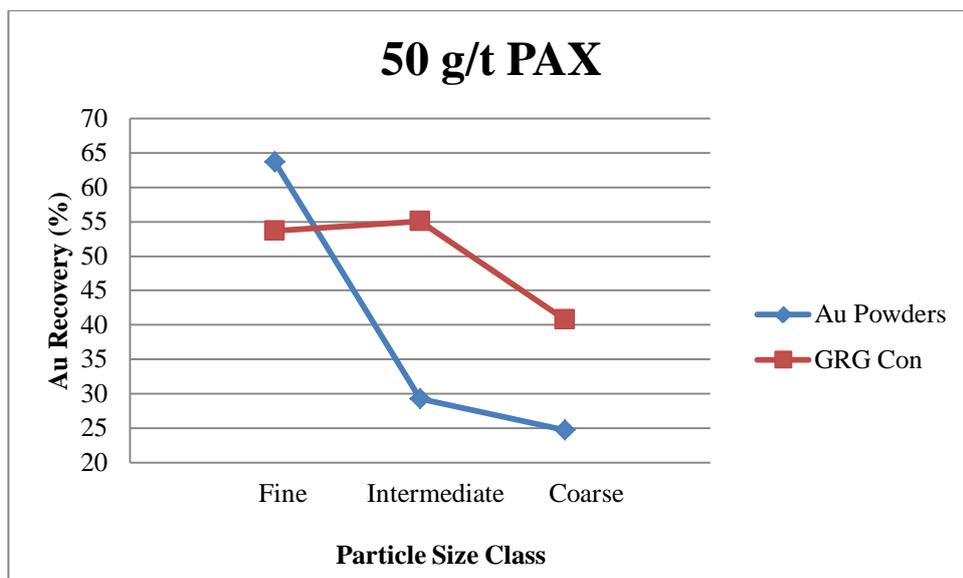


Figure 5-8. Fractional flash flotation period recoveries per size class of GRG concentrate and Au powder as a function high PAX addition

5.2.5 Recoveries with Moderate Collector Dosage

The recoveries of gold with 25 g/t PAX addition, given in Figure 5-9, are important because this level of collector addition is similar to industrial flash flotation reagent dosage and has demonstrated good free gold recovery in previous experiments.

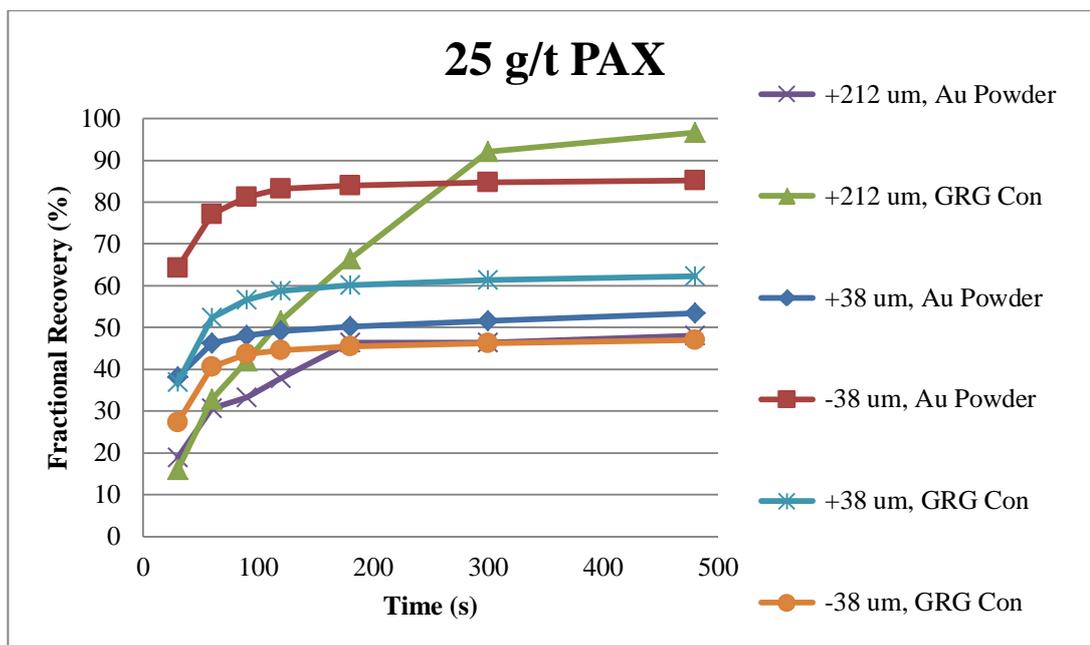


Figure 5-9. Fractional recoveries of particles from GRG concentrate and Au powder at 25 g/t PAX addition

Figure 5-9 reveals opposite trends of improved recovery for some particle types. For example, GRG particles yielded better recovery with increasing particle size while decreasing Au powder particle size improved recovery. This means the coarse fraction of GRG concentrate and the fine fraction of Au powder particles achieve the highest recoveries when adding 25 g/t PAX. While kinetic trends appeared similar to the 50 g/t PAX addition tests, the flash flotation period fractional recoveries were higher particularly in the case of the Au powder particles, as demonstrated in Figure 5-10.

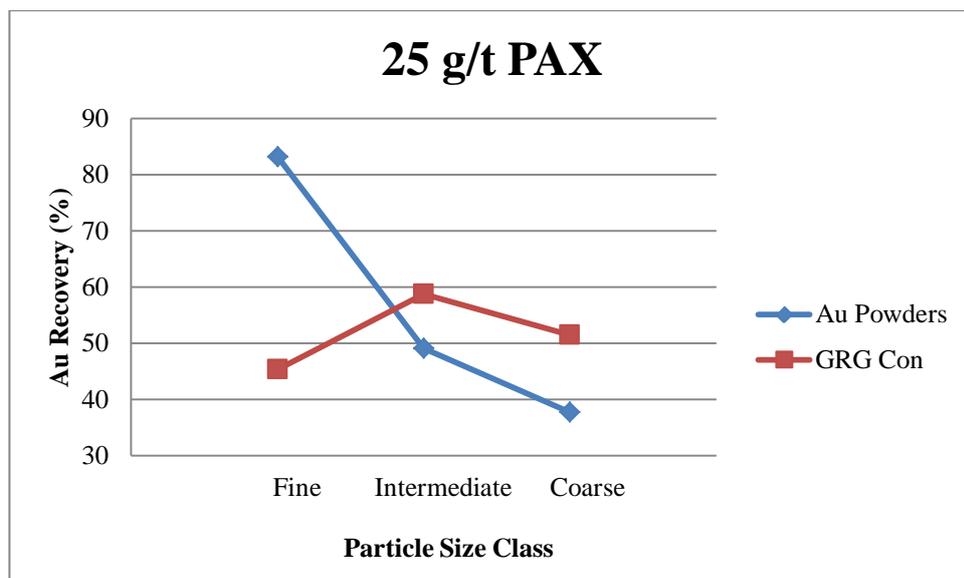


Figure 5-10. Fractional flash flotation period recoveries per size class of GRG concentrate and Au powder as a function moderate PAX addition

5.2.6 Recoveries in Absence of Collector

Collectorless flotation results, presented in Figure 5-11, are important because they reveal the differences in the two particle type's inherent floatability under the given conditions. It is important to note that the laboratory testwork in this thesis used Perth tap water and not plant process water. Process water is likely to have impurities such as organics or cyanide species which may act to unintentionally collect or depresses various components of the pulp.

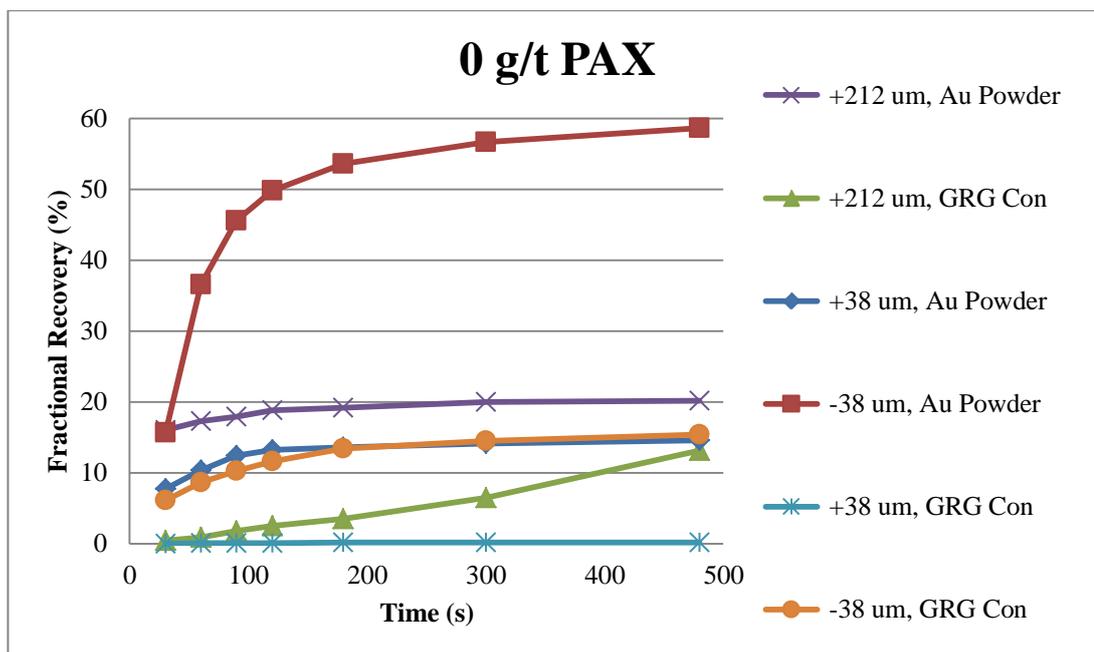


Figure 5-11. Fractional recoveries of particles from GRG concentrate and Au powder at 0 g/t PAX addition, i.e. collectorless flotation

In the absence of collector the fine particles in the Au powder were recovered better than the GRG concentrate in all particle size classes. The fine particle recovery in collectorless flotation conditions was superior to the intermediate and coarse fractions for both synthetic ores tested. Overall, superior recovery was noted for the synthetic Au powder particles by collectorless flotation when compared to the GRG concentrate free gold particles of similar size fractions. This is particularly clear in the case of fine particles, as can be seen in Figure 5-12.

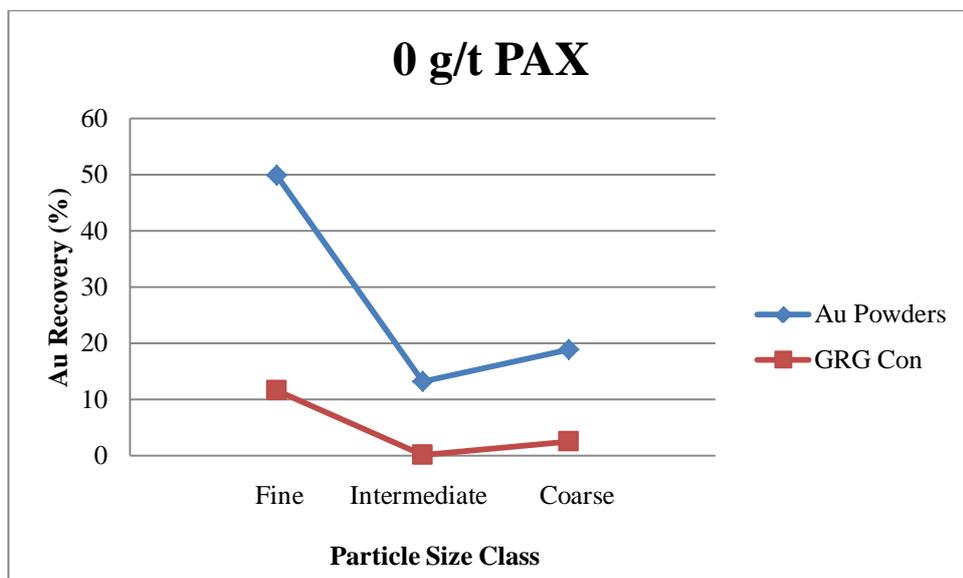


Figure 5-12. Fractional flash flotation period recoveries per size class of GRG concentrate and Au powder in absence of PAX addition

5.2.7 Au Powder Recoveries

The effect of varying PAX additions for all Au powder particle sizes of interest is given in Figure 5-13. This information is of interest as it gives baseline, theoretical recoveries for unmilled, pure gold particles displaying various shapes in the size ranges of interest.

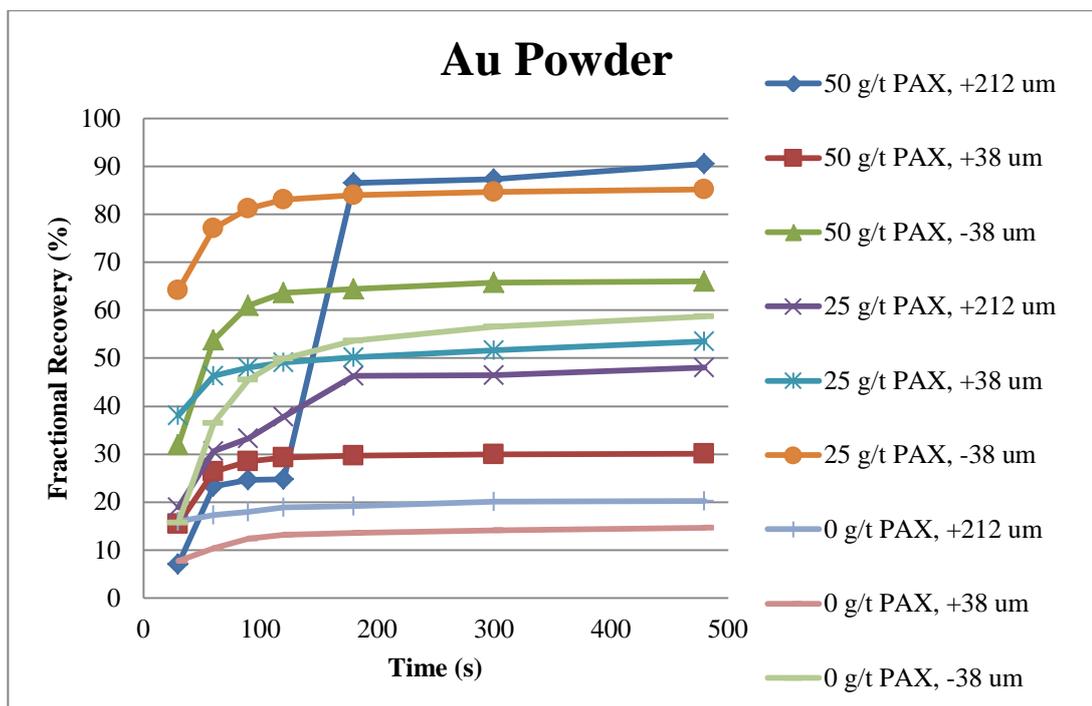


Figure 5-13. Fractional recoveries of Au powder at varying PAX additions

As indicated by the data, fine Au particles were most often recovered better than larger sizes, regardless of PAX addition, and especially in the case of collectorless flotation. These data agree with the findings of Lins and Adamian (Lins and Adamian, 1993) that demonstrated small particles of free gold floated using only a frother, while larger particles required the addition of a collector. The coarse particles with 50 g/t of PAX addition and fine particles with 25g/t of PAX addition were best recovered in the Au powder data set, though intermediate particle recovery decreased with 50 g/t PAX addition. This may be attributed to an over dosage of collector which could have adverse effect on recovery. Multi layers formed on particles reduce the proportion of nonpolar groups oriented towards the slurry, effectively decreasing hydrophobicity when compared to a monolayer of coverage.

5.2.8 GRG Concentrate Recoveries

As mentioned by Dunne (2005), the impact of milling on the floatability of free gold particles has been an issue of past debate. It was suggested by Taggart

(1945) and Pevzner et al. (1966) that milling may decrease a gold particle's ability to be recovered by flotation because of the impregnation of gangue material. Pevzner et al. (1966) also proposed passivation of the gold surface during milling would lead to reduced flotation recoveries. In contrast, Allan and Woodcock (2001) hypothesised that work hardening of gold particles during milling could activate gold particle surfaces and improve floatability. Work hardening will strengthen the surface of a metal by plastic deformation and can change the surface finish, meaning there is potentially an effect on the adsorption of collector. The effect of silver content acting to promote the flotation of GRG particles as compared to pure Au powder particles must also be considered as the GRG concentrate particles contain, on average, 10% silver. The effect of varying PAX additions for all GRG concentrate particle sizes of interest is given in Figure 5-14.

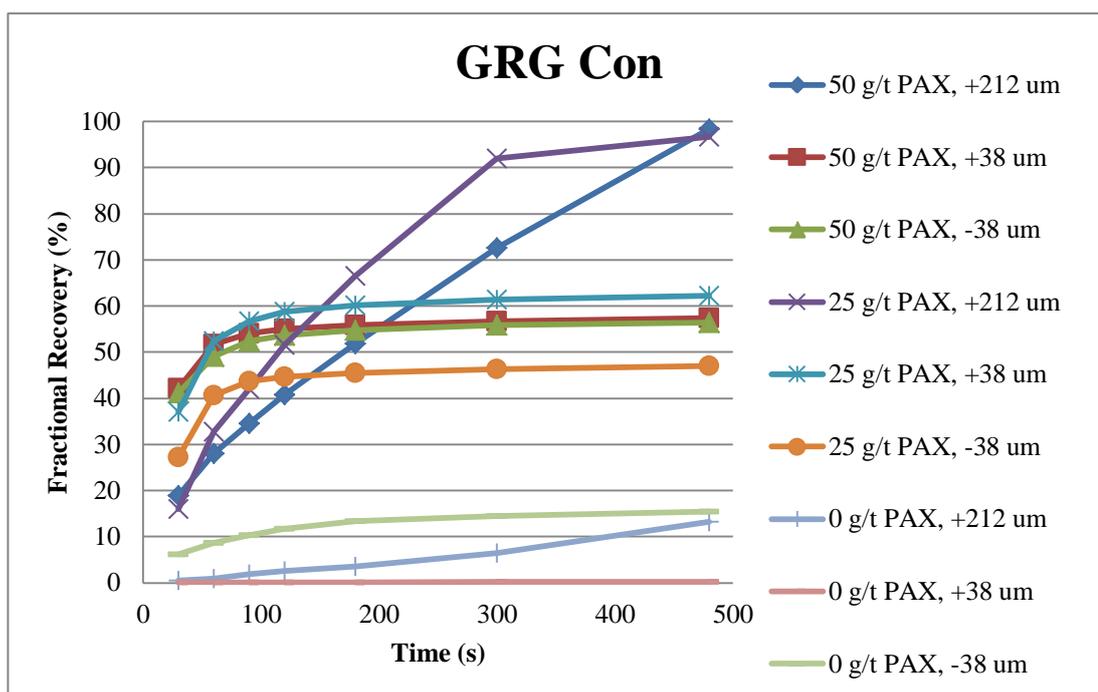


Figure 5-14. Fractional recoveries of GRG concentrate at varying PAX additions

This information is valuable because it can be used in comparison to the pure gold particle recoveries given in Figure 5-13 to demonstrate the influence of composition, milling and surface effects on the ability of PAX to float the free gold.

Data in this set are grouped into three regions in the fractional recovery graph (Figure 5-14). Despite showing slow kinetics, the first group, which contained coarse free gold from the GRG concentrate, reached the highest recoveries at the 50 g/t PAX and 25 g/t PAX additions. The middle group contained the fine and intermediate particles with both the 50 and the 25 g/t PAX additions. Interestingly, the intermediate particles were recovered similarly at either PAX addition level. The fine particles exhibit increased recovery with further PAX additions, which may indicate that over-ground particles require more PAX to achieve maximum recovery in flotation. While all GRG particles achieved poor recoveries in the flash flotation period without the addition of PAX; the intermediate GRG concentrate was not recovered at all without the addition of PAX. However, intermediate and fine GRG particles were recovered better than the coarse particles in the flash flotation period with PAX additions.

5.2.9 Ultimate Recoveries

The cumulative recoveries of each particle size as they contribute to the overall or ultimate gold recovery for each test condition are shown in Figure 5-15.

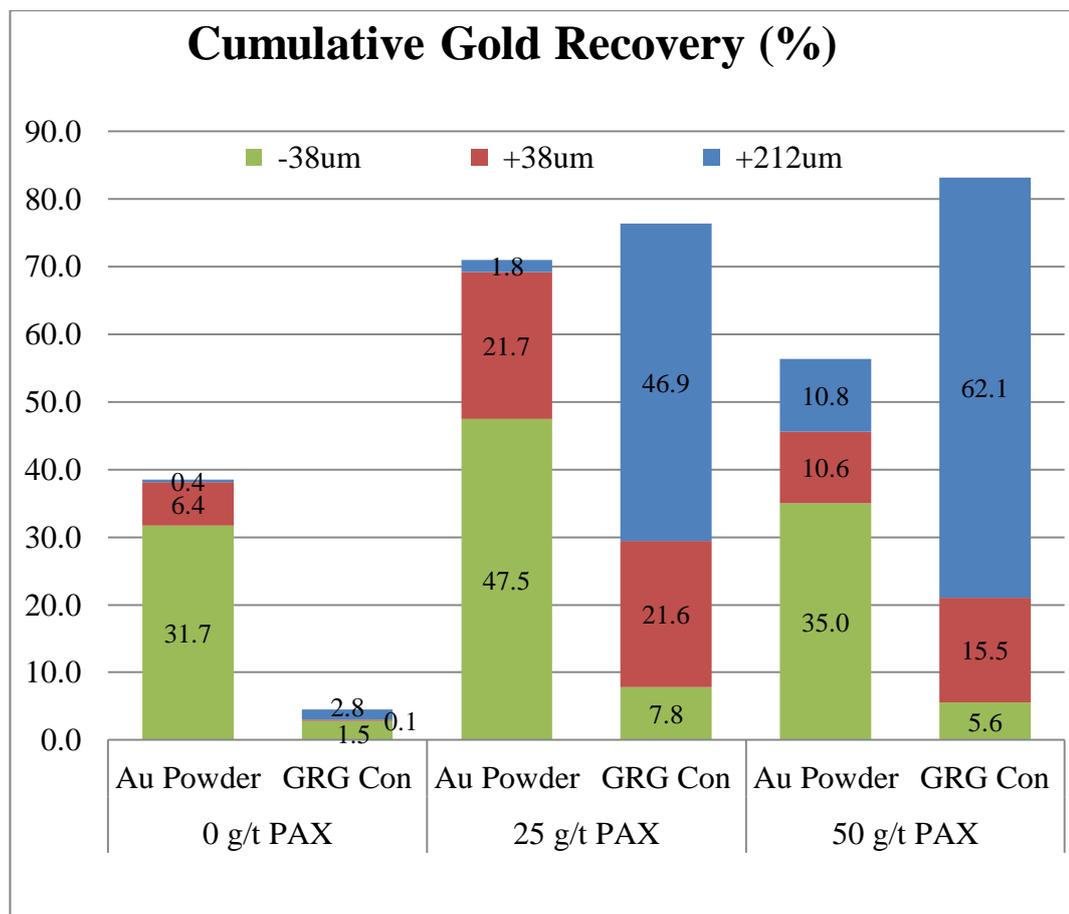


Figure 5-15. Recoveries of each size fraction as it contributes to the overall recovery achieved in each test condition for the GRG concentrate and Au powder at varying PAX additions

Although this figure does not include any kinetic information, it is the first time total recoveries for the laboratory flash flotation test have been given. Displaying the data in this manner makes it evident that the GRG concentrates as a bulk sample are more coarse than the Au powder. When data are reported in terms of total recovery, as in Figure 5-15, a few other trends are also evident.

- Firstly, the coarse particles float better with increasing PAX, especially in the case of the GRG concentrate.
- Secondly, the contribution of fine GRG particles to the combined recovery is surprisingly low and in all cases, the fine Au powder contributes more to the overall recovery than the comparative size fraction of GRG concentrate.

- Thirdly, the intermediate Au powder is recovered better than the intermediate GRG concentrate by collectorless flotation while the intermediate fractions of both powder and concentrate contribute similarly to overall recovery in the 25 g/t PAX test. The overall recovery of the Au powder particles passes through a maximum at 25 g/t PAX, but the value drops when PAX is increased to 50 g/t. Conversely, the highest overall recovery of GRG is noted at the highest level tested for PAX (50 g/t), and the combined recovery drops when collector dosage is lowered to 25 g/t PAX.

5.2.10 Flash Flotation Period Recoveries

Figure 5-16 shows cumulative recoveries for the first two minutes (represented by four data points) of the laboratory testing, as data in the flash flotation period are of specific interest in this study.

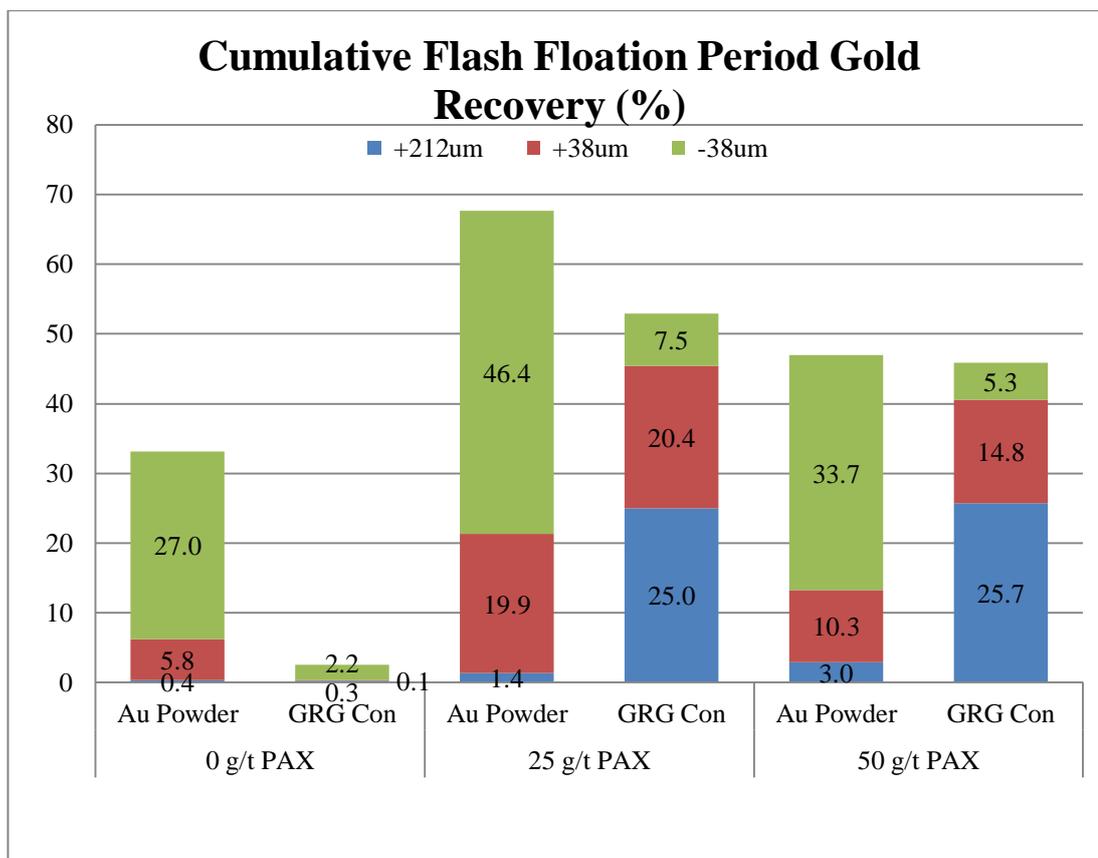


Figure 5-16. Recoveries of each size fraction as it contributes to the overall recovery achieved in the flash flotation period of each test condition for the GRG con and Au powder at varying PAX additions

A couple of trends are noted when comparing the flash flotation period flotation data given in Figure 5-16 to the overall recoveries shown in Figure 5-15. Interestingly, the trend of increased recovery of fine GRG with increased residence time is evident. Yet, this trend was not so evident for the coarse and intermediate GRG or any of the Au powder particles. Fine particles may require more conditioning time and thus display slower flotation kinetics than intermediate particles because their large surface area (in relationship to particle volume) requires high reagent consumption. Trahar (1981) suggests that poor ultimate recoveries of fine particles are purely due to physical constraints, specifically a poor collision efficiency with air bubbles.

5.2.11 Kinetic Modeling of Flotation Results

Values for the kinetic trends seen throughout this chapter have been calculated using the method of least squares to fit the coefficients in the given equation and the Solver function in Microsoft Excel to solve for unknowns, as was done in Chapter 4. Figures which demonstrate the model's fit to the generated data are given in Appendix 9.4. The kinetic data for all three models are presented in Table 5-1.

Table 5-1. Kinetic data for each type of gold particle type at varying PAX concentrations (units for k in min⁻¹)

Experimental ID	2 Component					3 Component (fixed)							3 Component						
	k _f	α _φ	γ _f	MAPE	AIC	k _f	k _s	α _φ	β _s	γ _f	MAPE	AIC	k _f	k _s	α _φ	β _s	γ _f	MAPE	AIC
50 g/t PAX Au Powder	0.72	0.24	0.76	37.88	15.70	0.72	0.36	0.24	0.00	0.76	37.88	15.70	0.72	0.72	0.24	0.49	0.27	37.88	15.7
25 g/t PAX Au Powder	0.25	0.44	0.56	4.72		1.25	0.25	0.44	0.56	0.00	3.34		0.82	0.25	0.44	0.56	0.00	4.73	
0 g/t PAX Au Powder	0.56	0.24	0.76	3.99	-49.34	0.56	0.11	0.24	0.00	0.76	2.32	-66.41	0.56	0.56	0.24	0.46	0.29	0.49	-101
50 g/t PAX BCC Con	1.12	0.16	0.84	10.28		1.21	0.24	0.14	0.07	0.79	10.28		1.19	0.10	0.11	0.08	0.81	10.28	
25 g/t PAX BCC Con	0.78	0.40	0.60	4.53		0.78	0.16	0.40	0.00	0.60	4.53		0.78	0.46	0.40	0.00	0.60	4.53	
0 g/t PAX BCC Con	0.36	0.17	0.83	33.72		1.80	0.36	0.17	0.83	0.00	33.52		0.36	0.36	0.17	0.62	0.21	34.58	

An assessment of the model's fit to the data for individual experiments can be made by comparing mean absolute percentage errors (MAPE). A high MAPE value indicates a poor fit to the model where a low value is indicative of a better fit. Akaike Information Criterion (AIC) values are presented for a high and low MAPE value in this data set. When the MAPE value is high the AIC values are the same, demonstrating any of the three kinetic models can be used to fit the data. When the MAPE value is low there is a larger deviation in the AIC values between the three models with the three component model having the lowest AIC value. As with the kinetic data presented in Section 4.2.2, the lowest AIC values are associated with minimised MAPE values suggesting the three component kinetic model is the best fit for this data set as well. It is important to note the high MAPE values, like those seen in the +212 μm data, show poor fit for estimation of kinetic values which is likely

due to sampling errors consistent with the nugget effect. Again, examples of data fit to the models can be found in Appendix 9.4.

The α , β and γ coefficients are useful in comparing the amount of material recovered in each data set. Analysis of these coefficients and the kinetic rate data reveal that a majority of the floatable intermediate and fine Au powder and GRG concentrate particles were characterised by the fast floating portion (γ_f) while the remainder of the gold particles contained in the pulp reported to tails (α_\emptyset), leaving hardly any material in the slow floating (β_s) category. In the case of GRG, it can be seen that an increased PAX addition yields faster kinetic rates and a shift in the proportion of recoverable material reflecting increased total recoveries. While the pure gold demonstrates faster kinetics at the 0 and 25 g/t PAX additions, the trend is for a decreased proportion of nonfloating material present at the higher PAX dosage. As can be expected from a pure component without surface modification, the lack of a slow floating portion was more pronounced in the Au powder particles than in the GRG concentrate. The fast floating portion of GRG in the -38 μm fraction increased with increased PAX addition, however the slow floating portion of GRG in the -38 μm fraction remained similar, despite changes in PAX levels. The +212 μm fraction of GRG fraction had a large portion of slow floating material, which was also not decreased by the addition of PAX to the system.

A comparison of the k values for free gold and pure gold flotation produced in this study (Table 5-1) and the sulfide and gangue flotation rates given in Table 2-4 (Kallioinen and Niitti, 1985) demonstrates that gold has faster flotation kinetics, making it a better candidate for flash flotation recovery. The kinetic results from this study also demonstrate that the particles in the pure gold powder are better recovered in collectorless flotation suggesting the milled particles may possibly have had deleterious surface coating or shape changes as a function of progressive comminution.

5.3 Summary

This chapter has identified the effect of collector dosage and gold genesis upon recovery and it has been established that there are differing responses across the size classes of interest with respect to the variables studied.

This work demonstrates the recovery of FRFG can be enhanced with increased concentrations of PAX, as clearly shown in the overall recovery data. Overall, superior recovery is noted for the synthetic Au powder particles by collectorless flotation when compared to the GRG concentrate free gold particles of similar size fractions. Even though the Au powder particles are better recovered by collectorless flotation than the GRG concentrate, unlike the GRG concentrate, they also demonstrated a greater decrease in overall recovery when the PAX addition was increased from 25 g/t to 50 g/t.

As predicted by Trahar (1981), higher coarse particle recoveries required additions of PAX, which was found to be true in this testwork for both FRFG and the Au powder particles. The insufficient recovery of coarse gold particles in flash flotation laboratory testing agrees with the findings of MacKinnon (2002) and Newcombe et al. (2012b) regarding coarse sulfide flash flotation trends.

The intermediate Au powder and GRG concentrate particles were recovered similarly in the lab float test with the collector PAX, although the Au powder particles displayed superior potential for collectorless flotation in this size range (as well as the other two size ranges) compared to the GRG concentrate. The superior inherent floatability of the unmilled Au powder particles in collectorless flotation suggested a possible deleterious effect of milling on the natural hydrophobicity of FRFG such as the imbedding of gangue or changes in shape as gold is progressively comminuted.

The fine Au powder particles were better recovered for all experiments than the GRG concentrate under corresponding conditions. The improved recovery of fine

GRG requires increased residence time and PAX addition to achieve acceptable recoveries.

The fit of several kinetic models was compared to the flotation data in this chapter, with the three component model selected as the preferred option. The kinetic evaluations indicate intermediate and fine gold particles from both sources were either recovered in the first 30 seconds or reported to tails. The kinetic data from this testwork suggest that fine and intermediate free gold particles will float faster than comparable sized sulfide and gangue materials, which agrees with other published studies (Kallioinen and Niitti, 1985). The increased ultimate recoveries of FRFG particles compared to flash flotation period recovery values demonstrate that improved total recoveries were achieved with additional collector and residence time.

The testwork in this chapter has demonstrated a varied response in free gold by flotation recovery based on size, collector dosage, residence time and gold genesis in the laboratory setting. The literature review presented in Chapter 2 suggests similar factors may influence the recovery behavior of free gold in an industrial setting with gravity and flash flotation operating in parallel, with a particular emphasis on the influence of size and shape.

CHAPTER 6. CHARACTERISATION OF FREE GOLD RECOVERED BY FLASH FLOTATION AND GRAVITY CONCENTRATOR UNITS IN PARALLEL OPERATION

6.1 Introduction and Background

The focus of the work described in this chapter was to study the recovery behaviour of free gold in an industrial setting with gravity and flash flotation operating in parallel, with an emphasis on the influence of size and shape. There was also an evaluation of the accuracy of stereological measurements from existing techniques for the quantification of free gold shape by comparing two and three dimensional (2D and 3D) methods and identifying the limitations of these applications. Ultimately, the aim was to determine if physical differences (like shape, size or elemental distribution within the particle) can be quantified with available techniques and used to characterise gold particles in gravity and flash flotation concentrates.

During three plant surveys, samples of BCC (Knelson and Falcon) and flash flotation concentrates were taken simultaneously in order to investigate the types of particles recovered by each while the units operated in parallel and received the same feed stream. The survey was performed at three sites (Tongon, Kanowna Belle and Telfer), each displaying different ore mineralogies and operational strategies.

Samples were prepared for QEMSCAN and Micro CT analysis to primarily study the size and shape impacts for gravity and flash flotation recovery. In the course of this testwork it quickly became evident that there was also a need to determine the type of preparation and analysis required that could accurately characterise and quantitatively report the data describing the gold particles and the low concentration of gold (even in concentrate samples) necessitated additional upgrading prior to study of a statistically significant number of particles. The upgrading of samples was performed by MagStream® separations and a reduction in the graphite dilution during QEMSCAN preparation.

6.1.1 Flash Flotation Comparison

In surveys conducted as part of the AMIRA P420 Gold Technology project the Kanowna Belle and Telfer flash flotation circuits were compared to other flash flotation circuits as summarised in Table 6-1 for the sake of benchmarking and comparisons. In a subsequent survey the flash flotation circuit at Tongon demonstrated 21.1 % GRG recovery in a 1.2 % yield to the concentrate (Wardell-Johnson et al., 2014).

Table 6-1. Flash flotation size recovery summary data from AMIRA P420D surveys (Wardell-Johnson, 2012)

Site	Flash Flotation Cell Type	Feed Stream	Concentrate Yield (%)	GRG Recovery (%)
Bulyanhulu 2006	Contact	Knelson Tail (CUF)	2.38	21.6
Kanowna Belle 2005	Mechanical	CUF	1.24	31.8
Telfer T1 Rougher	Mechanical	CUF	0.35	2.7
Telfer T1 Cleaner	Mechanical	Ro Con	19.52	86.8
Cadia	Mechanical	CUF	0.47	40.8
Ridgeway	Mechanical	CUF	1.35	43.6
Phoenix	Contact	Knelson Tail (CFeed)	0.21	27
Telfer T2 Rougher	Mechanical	CUF	1.22	34.2
Telfer T2 Cleaner	Mechanical	Ro Con	42.25	89.5

It can be seen that GRG recovery to the concentrate by flash flotation units is likely to be a function of ore type and, possibly, operational strategy as the recovery values fluctuate widely across the data set.

6.2 Results

6.2.1 QEMSCAN Round 1 - Telfer

The initial set of samples that were analysed by rare element scan (a setting designed to search for and map just the particles containing gold in the sample) via QEMSCAN were obtained from a survey around the gravity and flash flotation unit operations at Telfer. The survey produced a feed, concentrate and tails sample from each of the flash flotation and gravity unit processes; with two tails (coarse and fine) from the flash flotation unit. Each of the seven samples was wet screened into three size fractions (-600/+212 μm , -212/+38 μm and -38 μm) and diluted in a 3:1 ratio of graphite to sample mass for mounting in epoxy.

Feed samples and fine tails

Due to the low grade, no particles of free gold were detected in the Falcon or flash flotation feed samples, which were expected to be essentially identical as they were produced from the same feed material within the mill, having been sent to two hydrocyclones units with similar operational and design parameters. The fine flash flotation tail sample also contained no detectable gold particles. This was also anticipated since the fine tails outlet primarily acts to deslime and maintain water balance around the flash flotation unit. Due to the dilute nature of the solids in the stream, fineness of the particles and the low grade, little or no gold would be expected in this sample.

Tails

The gold particles detected in the coarse tails product of the flash flotation and the Knelson tails from the first round of QEMSCAN analysis are presented in Figure 6-1.

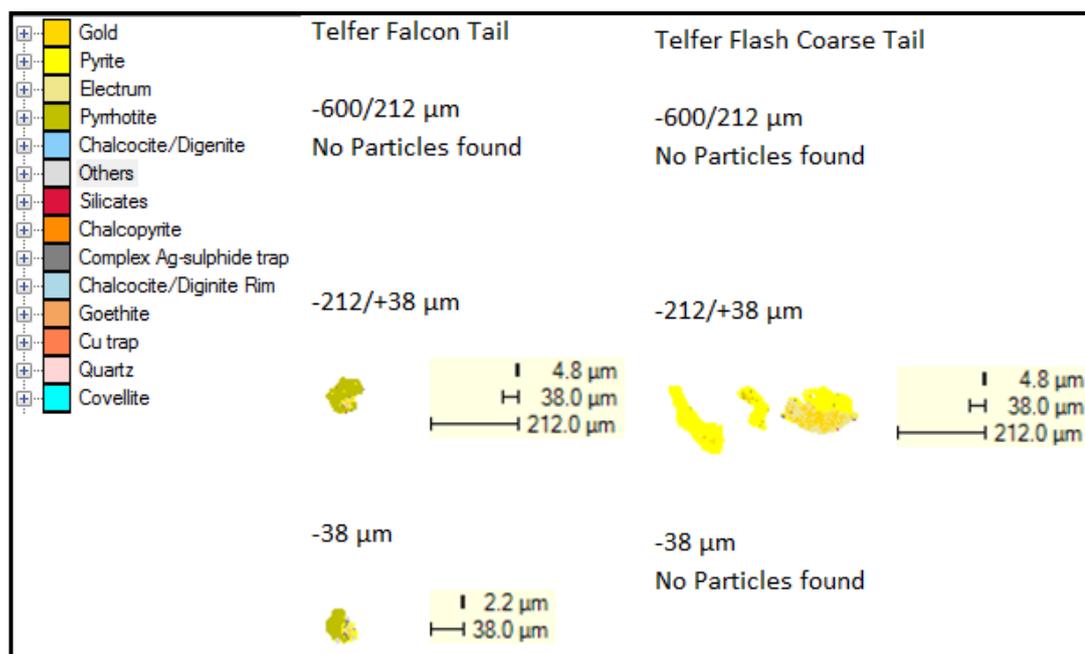


Figure 6-1. Gold particles in the Telfer Falcon and flash flotation tails as detected by QEMSCAN

As can be seen in Figure 6-1, no coarse gold particles were found in either the flash flotation or Knelson tails sample. Although the intermediate and fine particles which reported to the Falcon tail were roughly circular in shape (with spherical shaped particles speculated to be preferred in gravity recovery), the particles are primarily pyrrhotite and pyrite, not free gold. Coupled with their small size, the lower density of the sulfide minerals as compared to pure gold particles suggests those types of particles are less likely than coarse particles of free gold to be captured in a BCC concentrate. The flash flotation tails contained no detectable coarse or fine gold particles. This may be due to the low grade of the sample but is somewhat unexpected in the case of the fines as the flotation process has been suggested to best recover particles in this size range. Two of the three intermediate particles which reported to the flash flotation tails were mainly comprised of sulfides and display a flaky or elongated form, while the third was about half gold and/or electrum and round in two dimensional appearance. Again, this was of interest as particles of this size and composition were expected to float well, as noted in the literature and laboratory testwork. Possibly, the short residence time and lower reagent additions

typical of flash flotation were not favourable to flotation of intermediate particles which display lower flotation kinetics than fine particles of similar composition. In addition, previous surveys by the AMIRA P420 group (Wardell-Johnson, 2012; Wardell-Johnson and Bax, 2012a, b) indicate that, while Telfer operates their gravity circuit quite well, the flash flotation units would require better maintenance and plant operation in order to achieve ideal recoveries, as predicted by a characterisation of the GRG content in the ore.

Concentrates

During the first round of QEMSCAN analysis, only one particle was detected in the entire Telfer flash flotation concentrate sample (in the $-212/+38 \mu\text{m}$ size fraction) as compared to the many particles in the Falcon concentrate, shown in Figure 6-2.

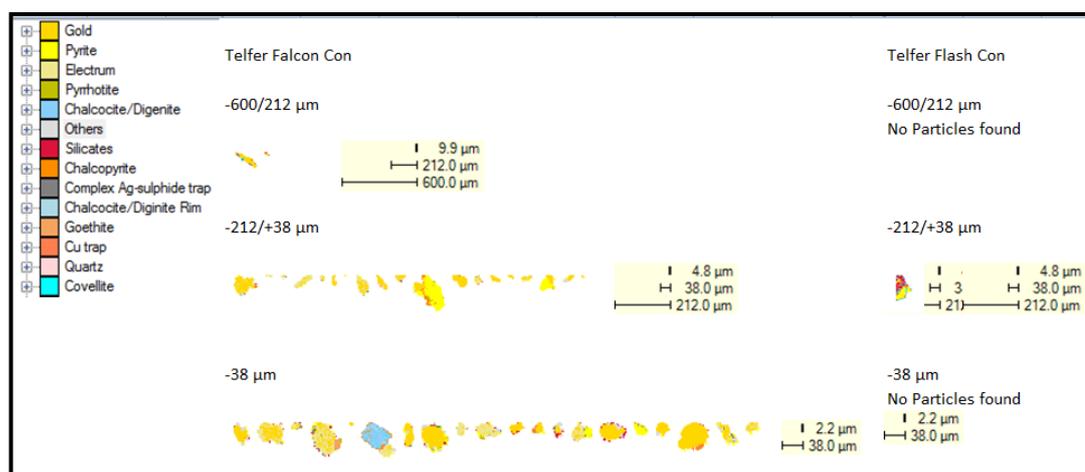


Figure 6-2. Gold particles in the Telfer Falcon and flash flotation concentrates as detected by QEMSCAN

The particles detected in the Telfer Falcon concentrate are predominantly comprised of gold, further supporting the existing concept that BCCs will recover free gold and that the sulfide content will act to reduce a gold particle's overall density and render it less amenable to BCC recovery. Interestingly, there were not many coarse particles in the Falcon concentrate but increasingly more particles in the

intermediate and fine size fractions. This is likely attributed to the size distribution of free gold in the feed material. Unfortunately, the lack of gold particles in the flash flotation concentrate material provided little to no insight about the types of gold particles recovered in this process. This is a function of both the low grade of the material and, possibly, the composition of the material recovered (i.e. free gold in the BCC concentrate versus possible gold in sulfides in the flash flotation concentrate).

6.2.2 QEMSCAN Round 2- Kanowna Belle and Tongon Concentrates

The second round of QEMSCAN analysis was prepared with a lower dilution factor (1:1) to increase likelihood of finding free gold because it had been identified that the low occurrence (grade) of free gold particles in the samples was the primary factor limiting the number of free gold particles detected. The second set of nine samples (sufficient to fill the QEMSCAN sample holder) was comprised of both the flash flotation and Knelson concentrates from Kanowna Belle as well as the flash flotation concentrate from Tongon which had been screened into coarse, intermediate and fine size fractions. The Tongon Knelson concentrate was not included at this time due to the capacity limits of the sample. This round of analysis was as much about validating the sample preparation method as acquiring data for analysis.

In Figure 6-3, images of the free gold particles are presented in two ways. First, general mineralogy of the gold containing particles is given in the colour and coincides with the listed key while the second set of images are of the same particles, though this time the gangue minerals are given a grey colour and gold is shown in red.

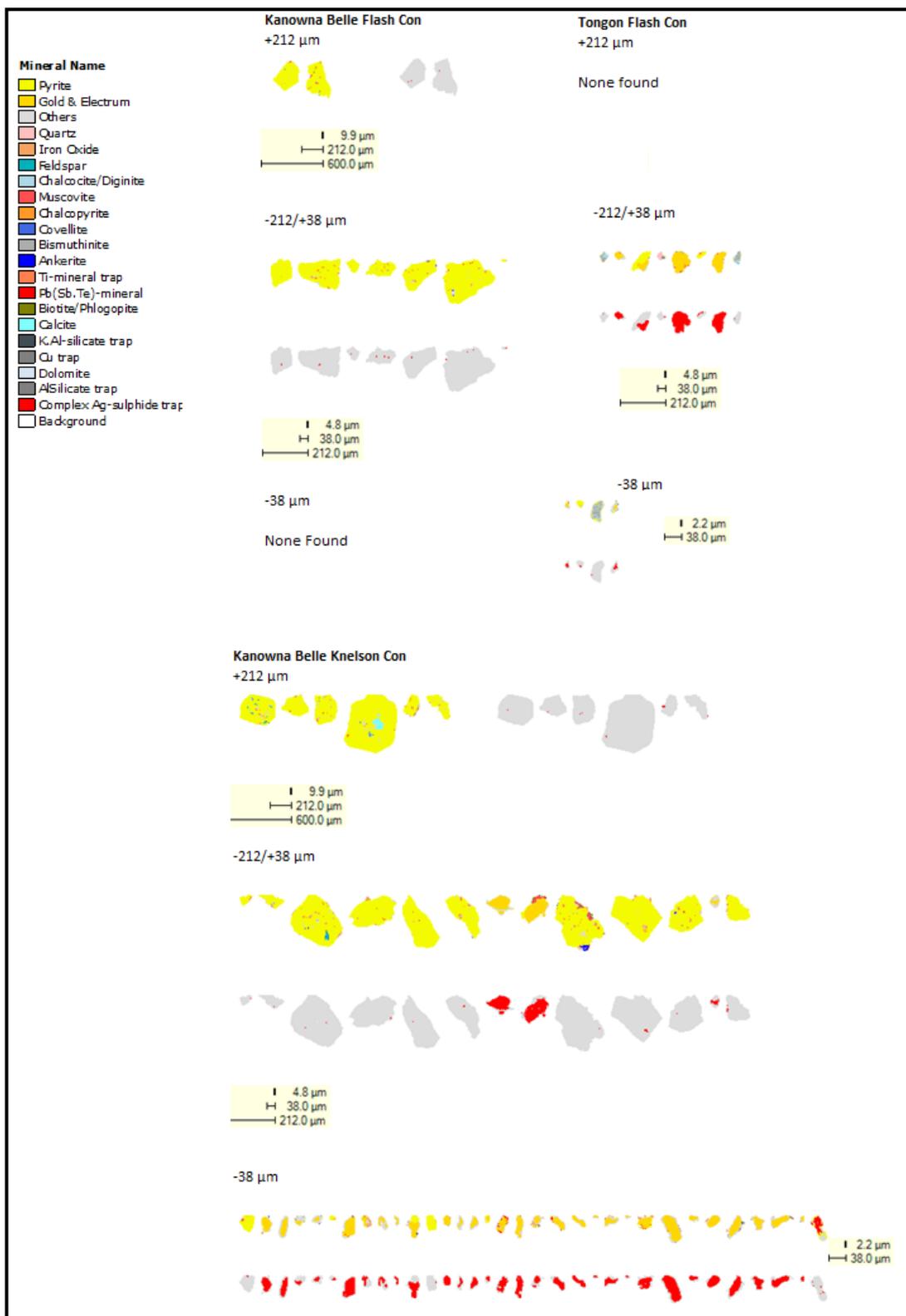


Figure 6-3. QEMSCAN results for the gold particles in the Kanowna Belle Knelson and Kanowna Belle/Tongon flash flotation concentrates

Although the Kanowna Belle flash flotation concentrate had two gold particles in the coarse fraction and several in the intermediate fraction, these particles were gold in sulfides not free gold as targeted for study in this project. Furthermore, no gold particles were detected in the fine fraction which was expected to contain the greatest occurrence of gold particles based on the literature review and laboratory flotation work conducted previously in this study. It is possible that this could have been explained by the coarse size distribution of the flash flotation feed material; however, this argument is not valid in this instance because the Knelson at Kanowna Belle received the same feed material as the flash flotation circuit and it recovered many more fine particles as compared to the flash flotation concentrate, demonstrating fine gold particles did exist in the milling circuit at the time of the survey. The fine fraction of gold particles recovered in the Kanowna Belle Knelson concentrate was largely comprised of free gold, while the larger particles (with the exception of two intermediates) were sulfides containing gold. The Kanowna Belle Knelson and flash flotation units are usually not operated in parallel, as they were for this survey. It took plant personnel weeks of adjustments to achieve stable operation of the two pieces of equipment in the milling circuit. Therefore, as with the case of Telfer, it is again possible that the operational parameters of the flash flotation circuit had not been optimised and greater numbers of particles could have been recovered if it were operating ideally.

The Tongon flash flotation concentrate captured a few intermediate particles with varying proportions of gold and even fewer fine particles which consisted of gold in carriers only. Further testwork on the Tongon ore has suggested the site was using a frother not suitable for the production of a shallow, yet stable froth as required in flash flotation operation (Wardell-Johnson et al., 2014). In addition, the site had very high WAD cyanide content in the plant water that could act to depress sulfide flotation and was potentially deleterious to free gold recovery.

6.2.3 QEMSCAN Round 3- Dense Particles in Concentrates

MagStream™ Upgrading

After a review of the Round 2 data, it was decided that the decreased graphite dilution during sample preparation was still not adequate to produce a sample containing a sufficient number of gold particles. A third set of -212+38 µm samples was upgraded by MagStream™ prior to further analysis by QEMSCAN and Micro CT. The separations achieved with MagStream™ from all three sites in this size fraction are reported in Table 6-2.

Table 6-2. Distribution for MagStream™ separations

		+6 SG				+4 SG			
		Feed	Lights	Heavies	Total	Feed	Lights	Heavies	Total
Kanowna Belle	Gravity Concentrate (g)	15.36	3.49	11.62	15.11	75.55	20.19	54.42	74.61
	<i>mass distribution (%)</i>		<i>23.10</i>	<i>76.90</i>			<i>27.06</i>	<i>72.94</i>	
	Flash Concentrate (g)	15.26	12.85	2.03	14.88	80.63	57.48	21.09	78.57
	<i>mass distribution (%)</i>		<i>86.36</i>	<i>13.64</i>			<i>73.16</i>	<i>26.84</i>	
Telfer	Gravity Concentrate (g)	14.18	9.56	4.49	14.05	33.69	9.8	22.91	32.71
	<i>mass distribution (%)</i>		<i>68.04</i>	<i>31.96</i>			<i>29.96</i>	<i>70.04</i>	
	Flash Concentrate (g)	9.97	8.52	1.27	9.79	24.61	7.89	16.09	23.98
	<i>mass distribution (%)</i>		<i>87.03</i>	<i>12.97</i>			<i>32.90</i>	<i>67.10</i>	
Tongon	Gravity Concentrate (g)	60.65	41.2	18.93	60.13				
	<i>mass distribution (%)</i>		<i>68.52</i>	<i>31.48</i>					
	Flash Concentrate (g)	84.39	40.8	43.1	83.9				
	<i>mass distribution (%)</i>		<i>48.63</i>	<i>51.37</i>					

Ultimately, the concentrates from Kanowna Belle and Telfer were upgraded by (approximately) a factor of 10 for the flash flotation and 4 for the BCC to produce the +6 SG fraction. In contrast, the same procedure rejected only half of the gangue material from the flash flotation concentrate and about two-thirds of the gangue from the BCC concentrate at Tongon.

The third and final round of QEMSCAN analyses was then carried out on the +6 SG fraction of the intermediate particles from the Tongon, Telfer and Kanowna Belle flash flotation and gravity concentrates. It is worth noting these same samples were the same +6 SG fraction of the intermediate concentrate particles which had first been used for the Micro CT portion of the study. The Micro CT analysis was non-destructive and allowed for more sample mass to be available for QEMSCAN in

this testwork. Again, the general mineralogy of the gold containing particles in the following data set (Figure 6-4-Figure 6-7) has been given in colour and coincides with the listed key while the second set of images are of the same particles, though this time the bulk gangue minerals are all given a grey colour and gold is shown in red.

Kanowna Belle

The QEMSCAN results for the Kanowna Belle survey demonstrate that, even after gangue rejection via MagStream™, the concentrate samples still contained very few free gold particles. The Knelson concentrate in Figure 6-4 contains a few more liberated gold particles than the flash flotation concentrate, though many were associated with pyrite. The flash flotation concentrate shown in Figure 6-5 only contains particles of gold in association with pyrite.

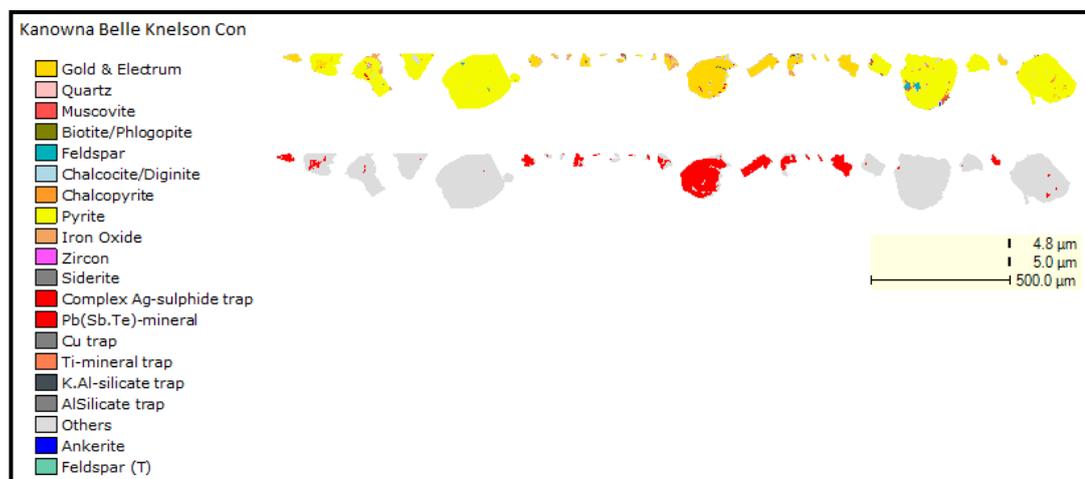


Figure 6-4. QEMSCAN results for the -212/+38 µm gold particles in the +6 SG fraction of the Kanowna Belle Knelson concentrate

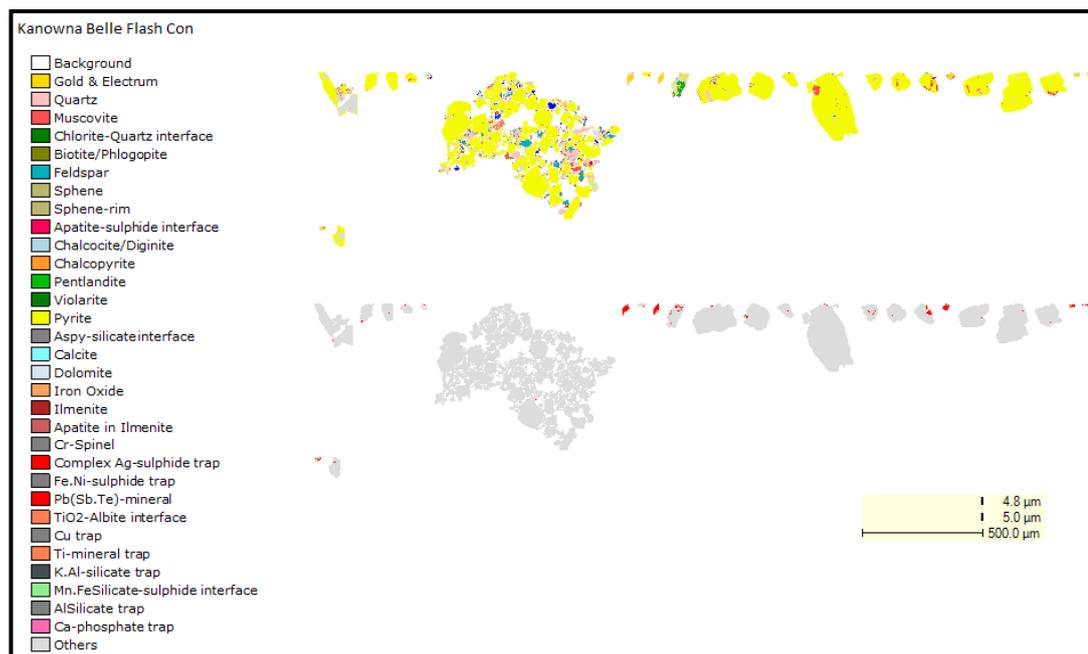


Figure 6-5. QEMSCAN results for the -212/+38 µm gold particles in the +6 SG fraction of the Kanowna Belle flash flotation concentrate

No data were found in this set of samples to support preferential flotation attributed to silver content/rimming. No 2D shape characterisations have been made on the Kanowna Belle concentrate samples due to the small number of free gold particles found by QEMSCAN.

Tongon

None of the particles analysed in the Tongon flash flotation concentrate (Figure 6-7) are fully liberated and only one appears in Figure 6-6 as free gold in the Knelson concentrate. This is likely due to Tongon's low GRG content, specifically in the coarse fraction.

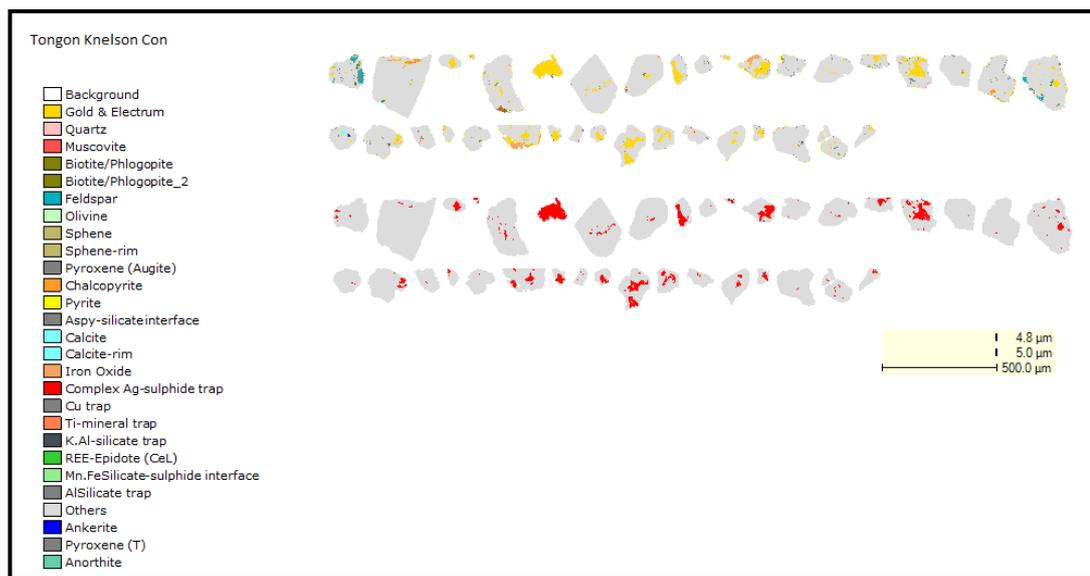


Figure 6-6. QEMSCAN results for the -212/+38 µm gold particles in the +6 SG fraction of the Tongon Knelson concentrate

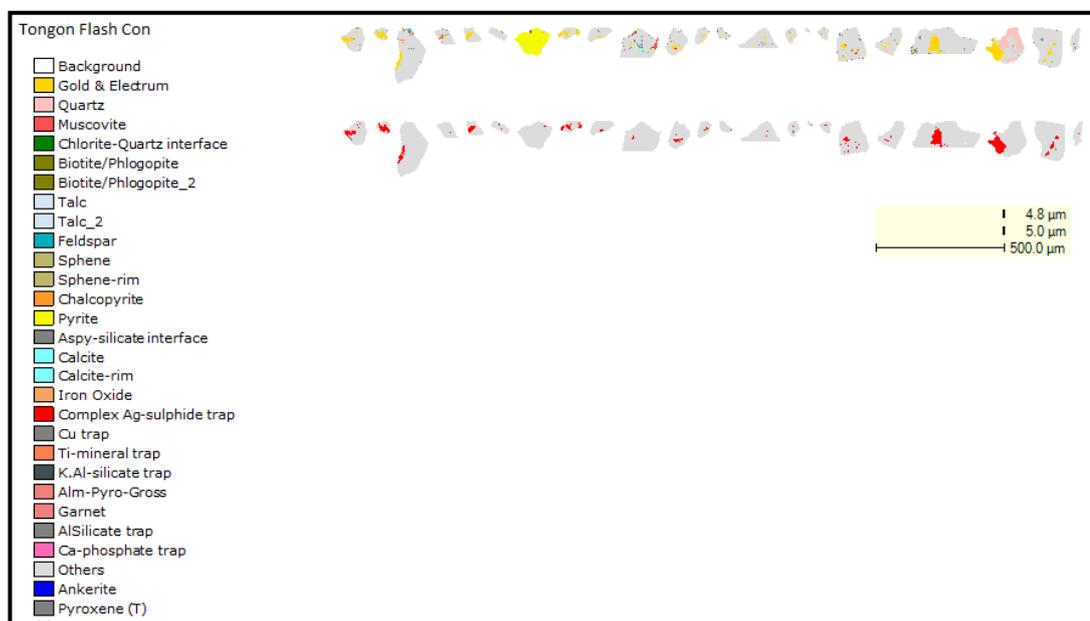


Figure 6-7. QEMSCAN results for the -212/+38 µm gold particles in the +6 SG fraction of the Tongon flash flotation concentrate

Again, there is no evidence in this data set to support or disprove the effect of silver content or rimming for preferential flotation and no 2D shape characterisations

have been made on the Tongon concentrate samples due to the limited number of free gold particles found by QEMSCAN.

Telfer

The gold particles from the Telfer Falcon concentrate were the most numerous of all the survey streams. Many of the gold particles in this sample were liberated although some were associated with sulfides. Interestingly, the QEMSCAN images reveal that several of the gold particles in the Falcon concentrate (Figure 6-8) were rimmed with a mineral identified as cobaltite and two contain a Pb-Te complex. As can be seen in Figure 6-9, none of the gold particles in the flash flotation concentrate appeared to have any rimming effects or contained the Pb-Te complex.

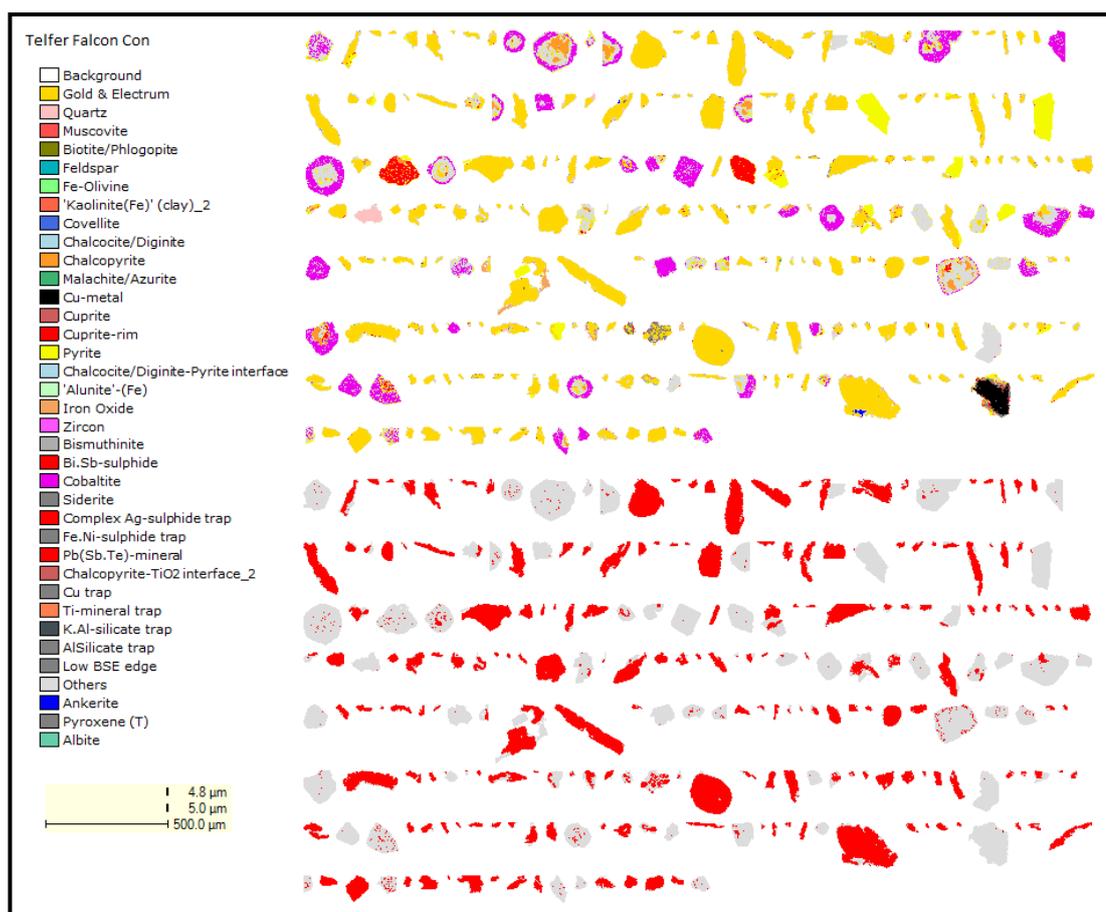


Figure 6-8. QEMSCAN results for the -212/+38 µm gold particles in the +6 SG fraction of the Telfer Falcon concentrate

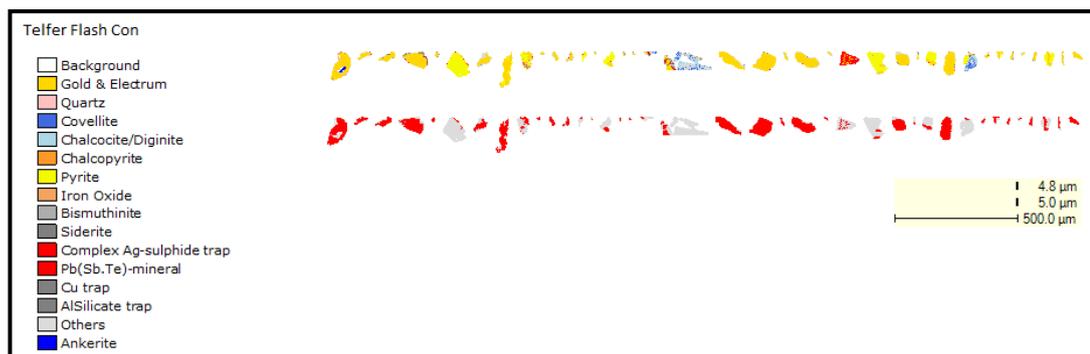


Figure 6-9. QEMSCAN results for the -212/+38 µm gold particles in the +6 SG fraction of the Telfer flash flotation concentrate

In contrast to the other two sites, many of the particles in the Telfer flash flotation concentrate were surprisingly well liberated, which is different from the flash flotation concentrates at other sites, though some exhibited a simple association with pyrite. A few particles in both concentrates were identified as electrum, but none with any specific rimming which might impact the floatability of the particle.

6.2.4 Comparison of the Concentrated Free Gold to the Bulk Sample from 2D QEMSCAN data

Comparisons of the size distribution and shape of the free gold particles in flash flotation and BCC concentrate samples to the bulk material were made only for Telfer as those samples contained the greatest number of free gold particles for analysis.

Size

While the data in Figure 6-10 and Figure 6-11 demonstrate a shift in decreasing coarseness of the size distribution when comparing the flash flotation particles to the Falcon particles, there is relatively no difference in size distribution for the free gold or gangue particles recovered in the same unit process. This is to say the free gold particles captured in flash flotation or BCC concentrates are no more coarse or fine than the + 6 SG fraction of the bulk material (comprised mainly of gangue) which was also recovered to the concentrate.

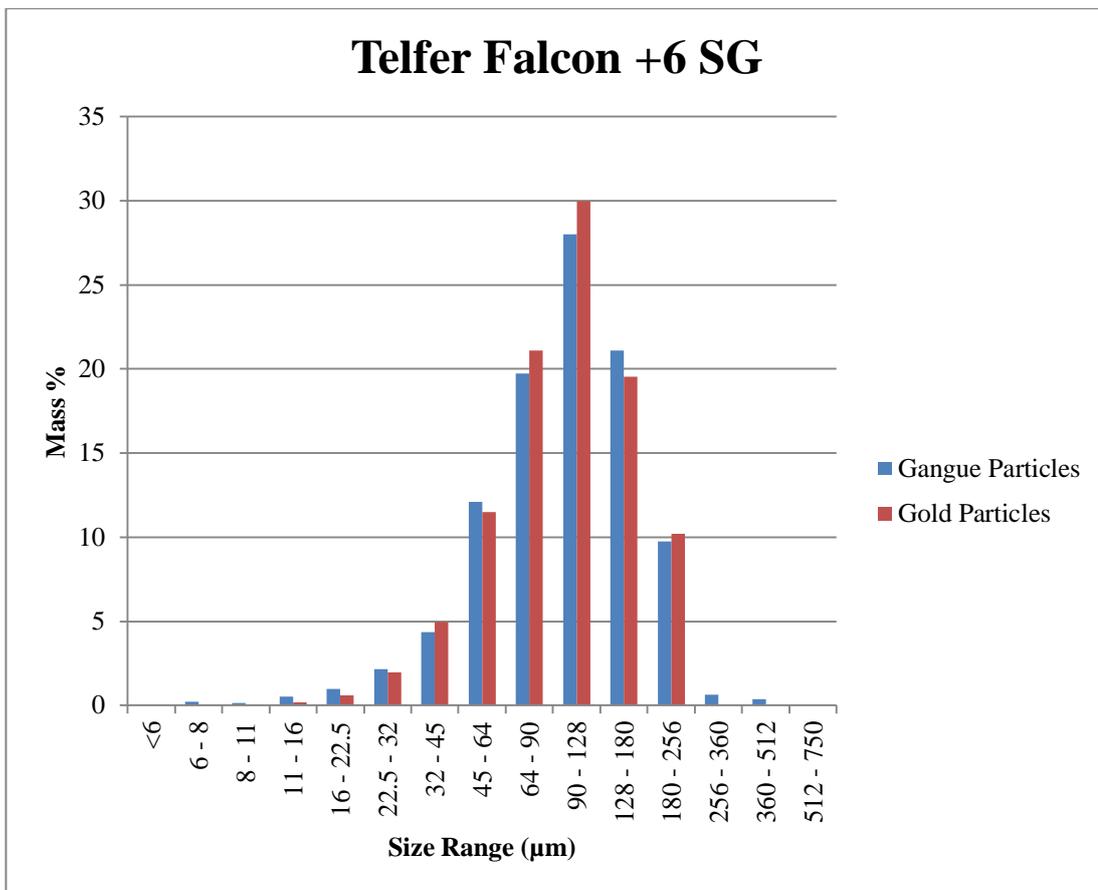


Figure 6-10. Size distributions of the free gold and gangue components in the +6 SG fraction of the -212/+38 µm Telfer Falcon concentrate sample

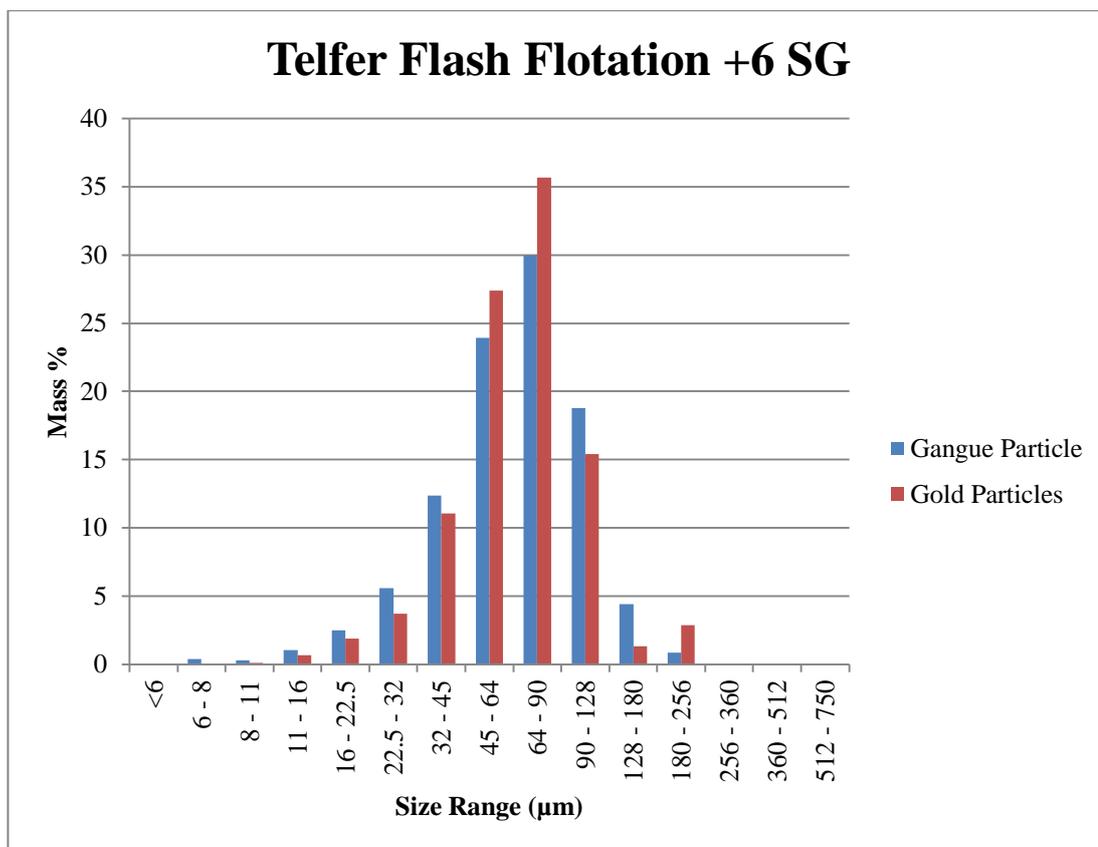


Figure 6-11. Size distributions of the free gold and gangue components in the +6 SG fraction of the -212/+38 µm Telfer flash flotation concentrate sample

Shape

Again, the Telfer samples were selected for 2D shape characterisations because of the abundance of free gold particles compared to the Tongon and Kanowna Belle samples. The 2D circularity measurements of the +6 SG fraction of the -212/+38 Telfer concentrate samples were performed by custom software using OpenCV Machine Vision Library. According to the software developer (Francis, 2014), Figure 6-12 through Figure 6-15 demonstrate how the software first marks the detected particle borders (red) followed by the minimum bounding rectangles for each of those particles (green ellipses) with major and minor axes set to the rectangle widths and heights. Note that these are fitted at whatever the best angle appears to be, which is not necessarily vertically.

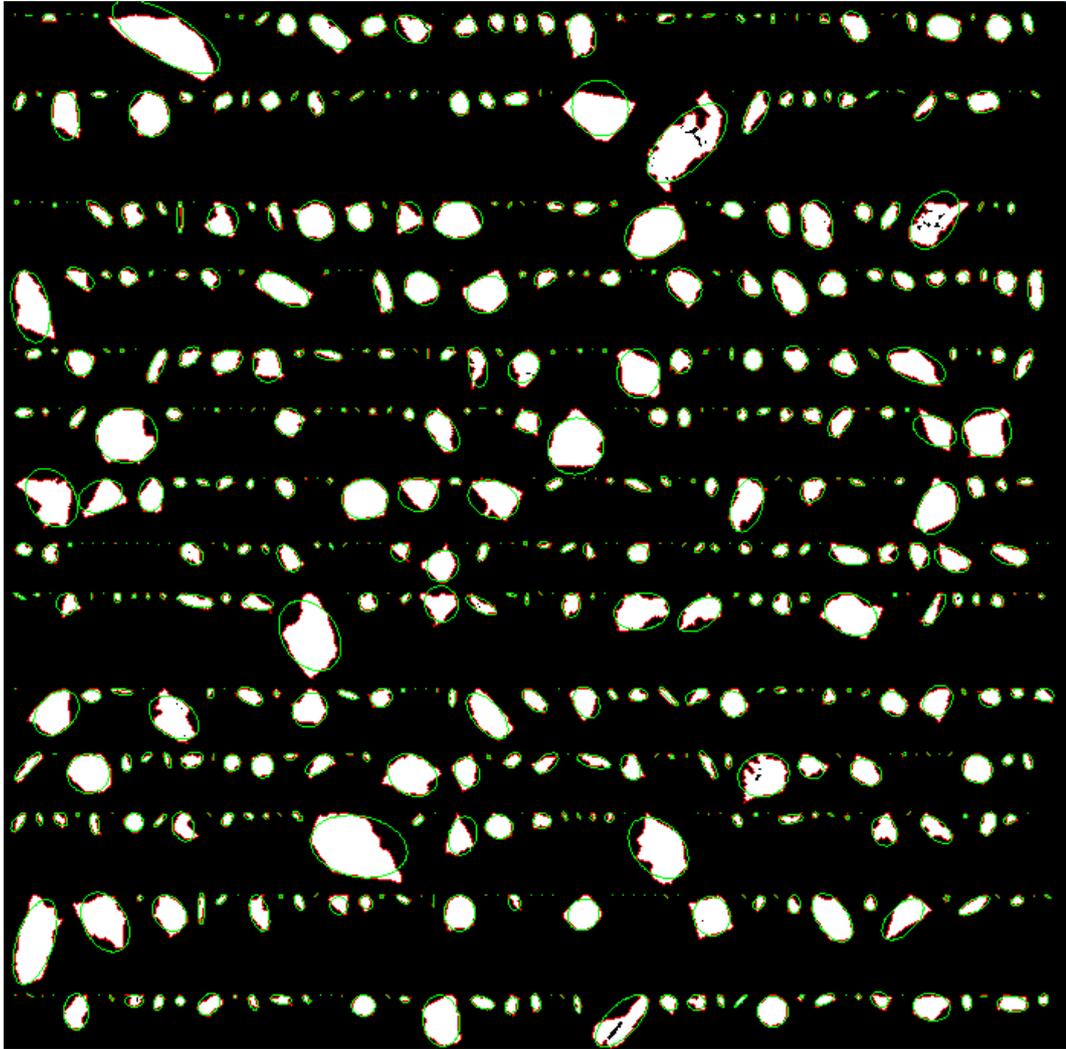


Figure 6-12. Images of particles in the Telfer Falcon concentrate bulk sample for 2D circularity calculations

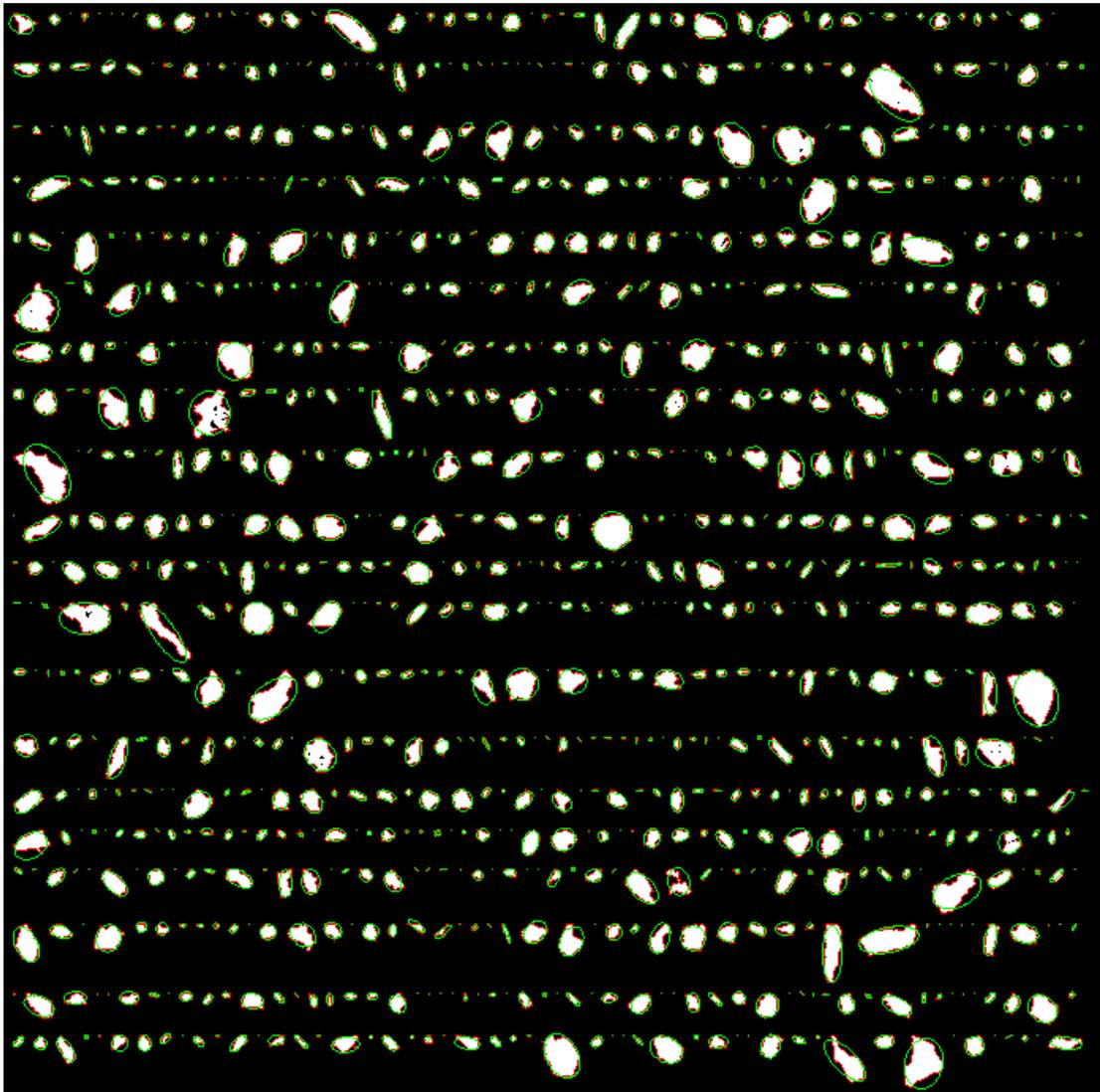


Figure 6-13. Images of particles in the Telfer flash flotation concentrate bulk sample for 2D circularity calculations

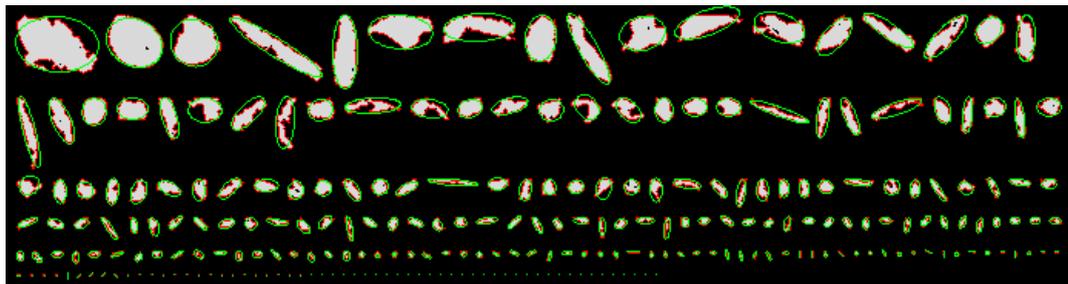


Figure 6-14. Images of gold particles in the Telfer Falcon concentrate bulk sample for 2D circularity calculations

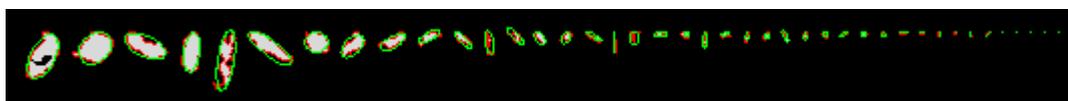


Figure 6-15. Images of gold particles in the Telfer flash flotation concentrate bulk sample for 2D circularity calculations

Cumulative circularity values are given in Figure 6-16 for particles identified as free gold as well as for the bulk material in the Telfer concentrate samples.

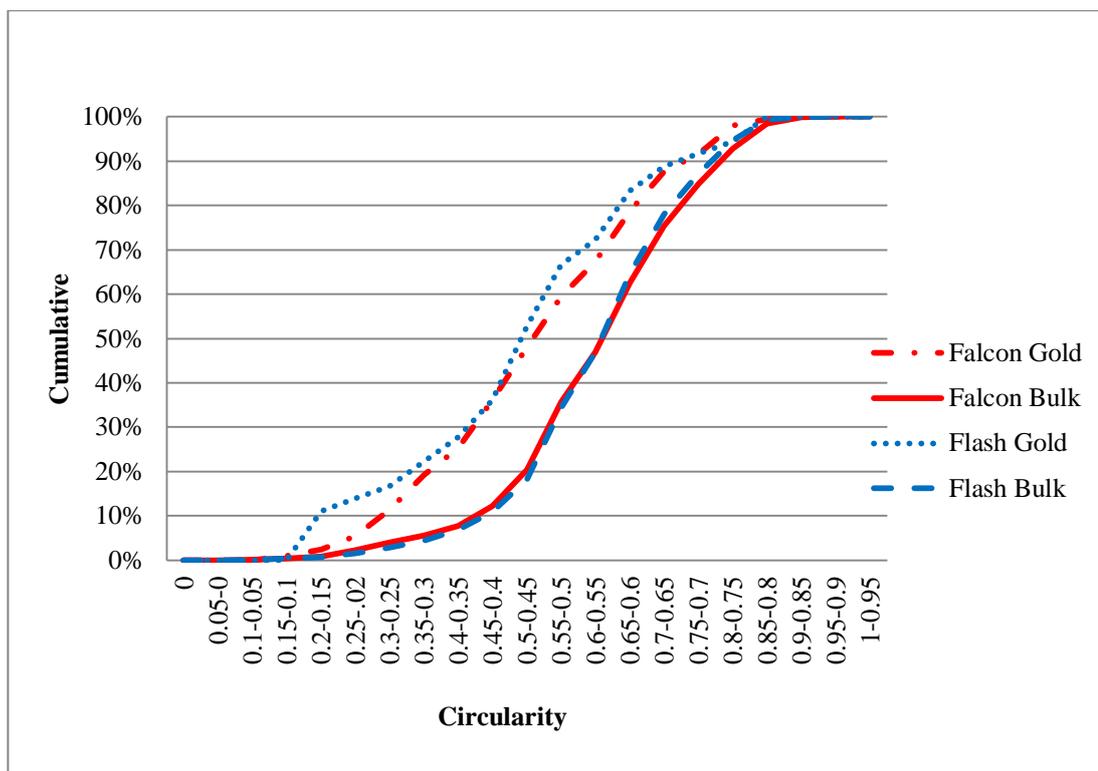


Figure 6-16. Circularity of free gold and the bulk material in the Falcon and flash flotation concentrates at Telfer

Comparison of gold circularity to the circularity of the bulk sample demonstrates that the free gold is less circular in 2D than the sample as a whole. This is the case for free gold particles identified in both the Falcon and flash flotation concentrates. While the bulk material demonstrates identical circularity in both concentrates, the free gold in the BCC concentrate is, on average, slightly more circular than free gold in the flash flotation concentrates. Unfortunately the sample size of free gold in the flash flotation concentrate is small (see Appendix 9.5 for histograms demonstrating particle counts in each circularity bin). The applicability of 2D measurements for the description of 3D gold particles is discussed in Section 6.3.

6.2.5 Comparison of the Concentrated Free Gold to the Bulk Sample from 3D Micro CT data

Initially, the BCC and flash flotation concentrates from Telfer, Tongon and Kanowna Belle were screened into $-212/+38 \mu\text{m}$ material for analysis by the Micro CT. It was quickly realised that the free gold grade was too low to contain sufficient

particles for the desired analysis. As a result, the +6 SG fraction of the -212/+38 μm material created from the MagStream™ separation of the BCC and flash flotation concentrates from Telfer, Tongon and Kanowna Belle were nondestructively analysed by Micro CT prior to mounting in epoxy for QEMSCAN. A blank sample was processed which contained a few particles of pure gold to act as a standard reference material for the plant concentrate samples. Measurements obtained by the Micro CT were used to calculate sphericity (Figure 6-17) and the Heywood volumetric shape factor (Figure 6-18).

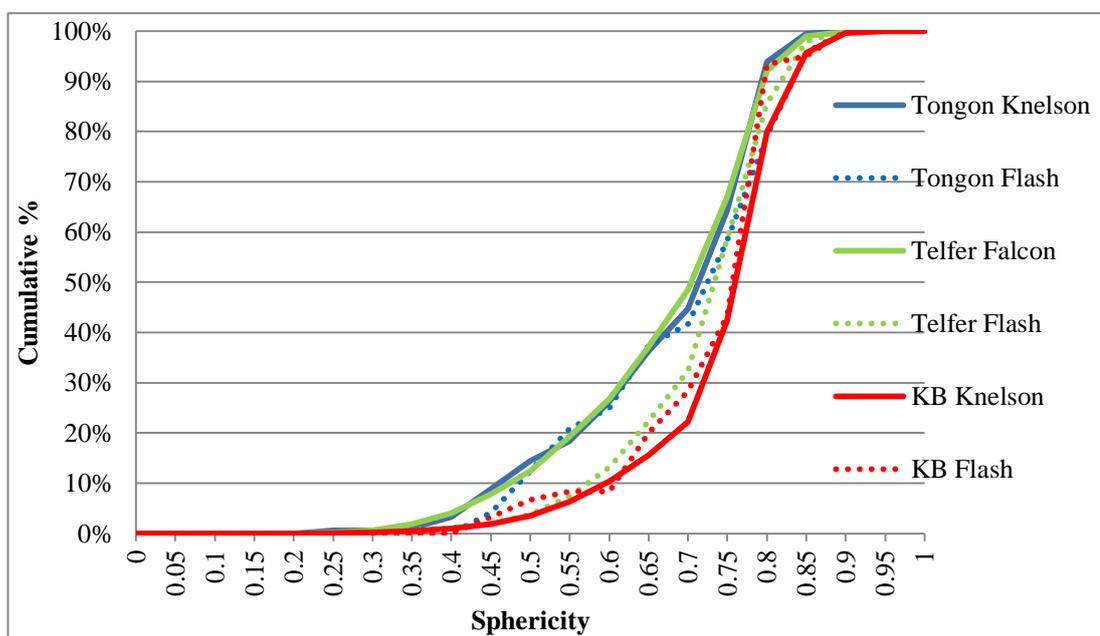


Figure 6-17. Sphericity of free gold particles in the concentrate samples

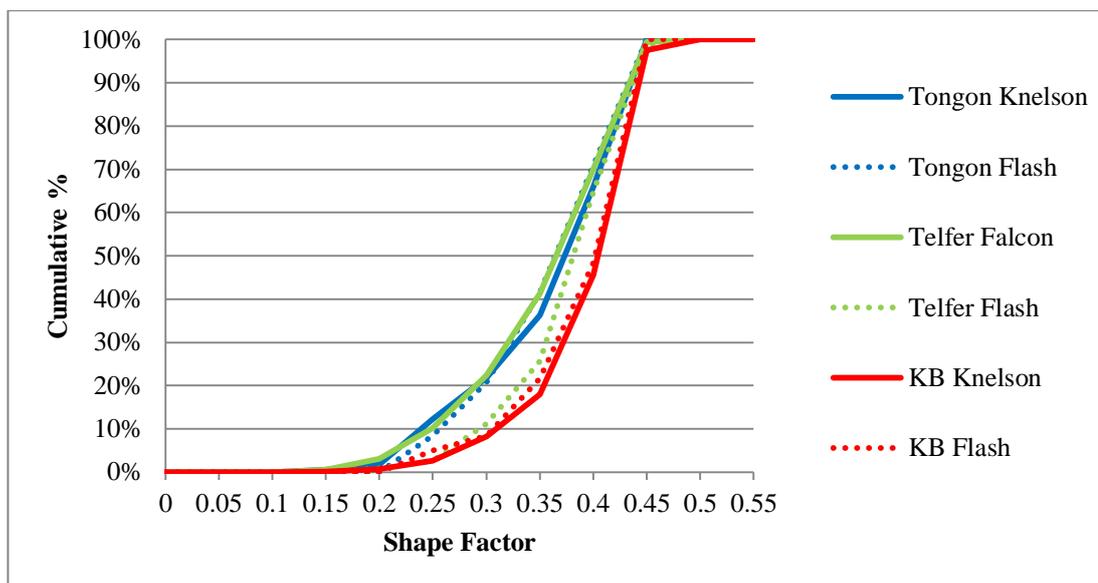


Figure 6-18. Heywood volumetric shape factor for free gold particles in the concentrate samples

The agreement of trends presented for sphericity and the Heywood shape factor in Figure 6-17 and Figure 6-18 suggest proper application of the methods and improbability of calculation errors. The sphericity and shape factors for each sample at the cumulative 50% mark have been interpolated (to demonstrate the median sphericity and shape factors) and are presented in Table 6-3 along with values for ideal shapes (Brown, 1991; Zeng, 2011).

Table 6-3. Sphericity and Heywood volumetric shape factors for free gold particles and ideal shapes

		Sphericity @ 50%	Shape Factor @ 50%
Tongon	BCC Con	0.740	0.395
	Flash Float Con	0.745	0.385
Telfer	BCC Con	0.725	0.390
	Flash Float Con	0.760	0.405
Kanowna Belle	BCC Con	0.780	0.430
	Flash Float Con	0.780	0.425
Ideal	Tetrahedron	0.671	
	Prism (x, 2 x, 3x)	0.725	
	Prism (x, 2x, 2x)	0.761	
	Prism (x, x, 2x)	0.767	
	Cone	0.794	
	Cube	0.806	
	Hemisphere	0.840	
	Sphere	1.000	0.5236

The data presented in Figure 6-17, Figure 6-18 and Table 6-3 indicate that the minimal difference in sphericity and shape factor noted between the concentrates of the BCC and flash flotation applications would have little, if any impact, of preferential shape in the -212/+38 μm size range for free gold at Kanowna Belle and Tongon. A measurable difference in free gold shape is noted at Telfer where, in contrast to the 2D circularity measurements, the free gold in the Falcon concentrate is less spherical than the free gold in the flash flotation concentrate. In fact, according to the sphericity measurements, the sampled concentrates appear to represent a prism type shape rather than anything spherical or rounded. Unfortunately, due to differences in grade, very few particles were measured in the case of the flash flotation concentrate while many thousands of particles were found in the BCC concentrate samples. Not only are the calculated shape and sphericity factors not very accurate in describing irregular gold particles, but descriptions may

be even less valid for the smaller sample size fraction. Histograms with particle counts in each fraction can be found in Appendix 9.5.

In reference to the Micro CT data, several further points should be considered. Firstly, it is possible the shape distribution of the feed particles was too fine and/or the samples were of an insufficient grade to demonstrate (qualitatively or quantitatively) much variation of shape in the particles recovered to concentrates. This seems particularly evident in that similar slopes are noted when comparing the shape or sphericity trends of the BCC and flash flotation unit concentrates at Tongon and Kanowna Belle. If an extensive variety of shapes is not present in the feed particle, then the two concentrators cannot use differences in shape for preferential recovery. Telfer is the only site which demonstrates a significant difference in shape or sphericity between the flash flotation and the BCC concentrates.

Secondly, it becomes apparent when, again, evaluating the shape and sphericity profiles for the Telfer concentrates that these two samples, produced from the same feed, show greater differences in shape/sphericity between them as compared to the other sites. This may suggest the feed particles have a greater distribution in shape and the concentrator units and therefore, shape may be given preference in recovery. But what is really interesting and contrary to the 2D data from Section 6.2.4 is that the Telfer shape/sphericity profiles suggest the Falcon recovery distribution includes flatter or elongated particles, while flash flotation recovers fairly spherical free gold particles. This is contrary not only to the previously presented 2D data but also to the popularly held belief that the BCCs will recover spherical particles and flash flotation will recover elongated or flattened particles, with other factors (i.e. density, size, composition) being similar.

Lastly, it is important to understand that the techniques for shape and sphericity quantification have historically been developed for and applied to particles with less irregularity than elements as malleable as free gold. It may not be practical to apply the simple calculations to data generated by the Micro CT software and obtain parameters with enough resolution to describe the dynamic shapes of the amoeba-like gold particles.

The following 3D images of gold particles (Figure 6-19 to Figure 6-26) have been generated from the Micro CT data and are presented to reinforce several points. Firstly, there is a vast difference in the grade and hence the number of particles analysed between the samples. Secondly, the shapes of gold particles are very irregular; some appear as smeared, filigree or even donuts and horseshoes. Visualisation of the particles in 3D space reiterates the inadequacy of the commonly used shape and sphericity calculations to describe their complex nature. And thirdly, it appears that some of the gold particles imaged were not entirely liberated and the shape of the aggregate particle may instead need to be investigated to deduce its effect on recovery.

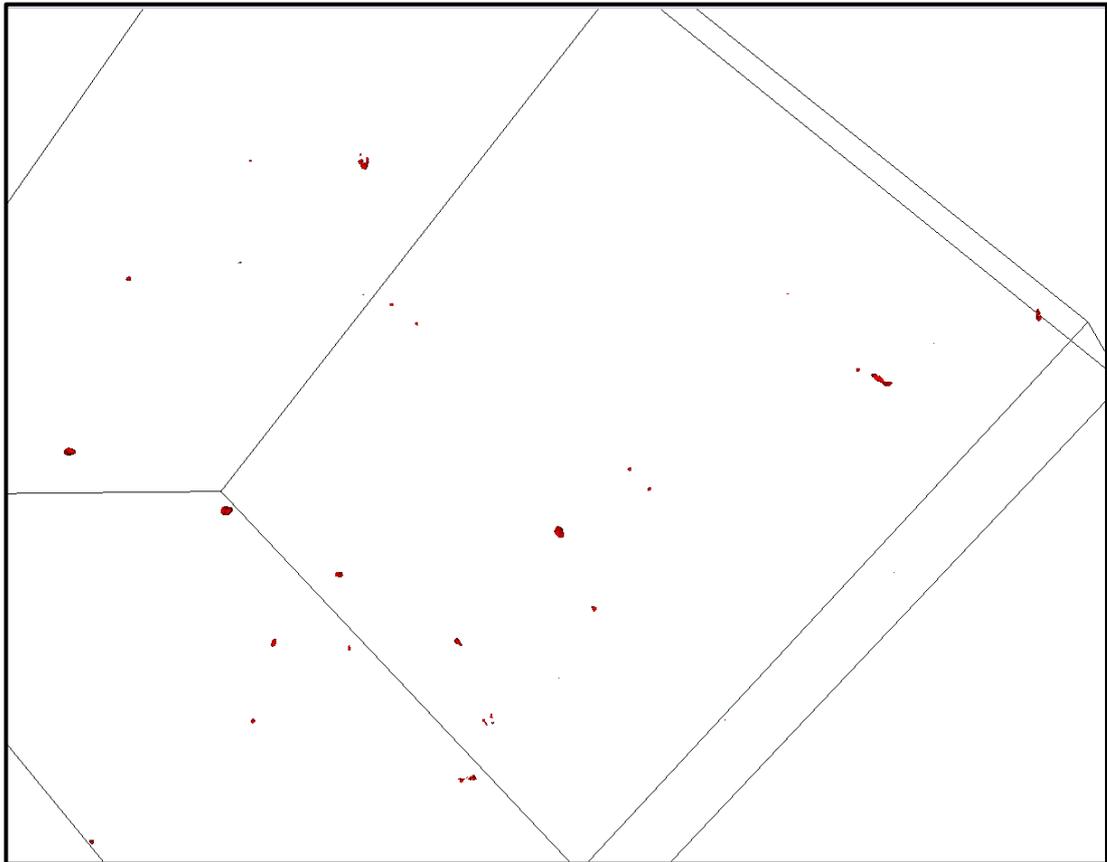


Figure 6-19. Micro CT images of -212/+38 μm gold particles found in the Kanowna Belle flash flotation concentrate

The Kanowna Belle flash flotation sample was upgraded by MagStream™ 11.3 times to form a +6 SG fraction. Despite the concentration efforts only 60 gold

particles were analysed by the Micro CT, which is still about ten times more than the best case QEMSCAN analysis. The particles yield an average calculated sphericity of 0.78 and an average volumetric shape factor of 0.425.

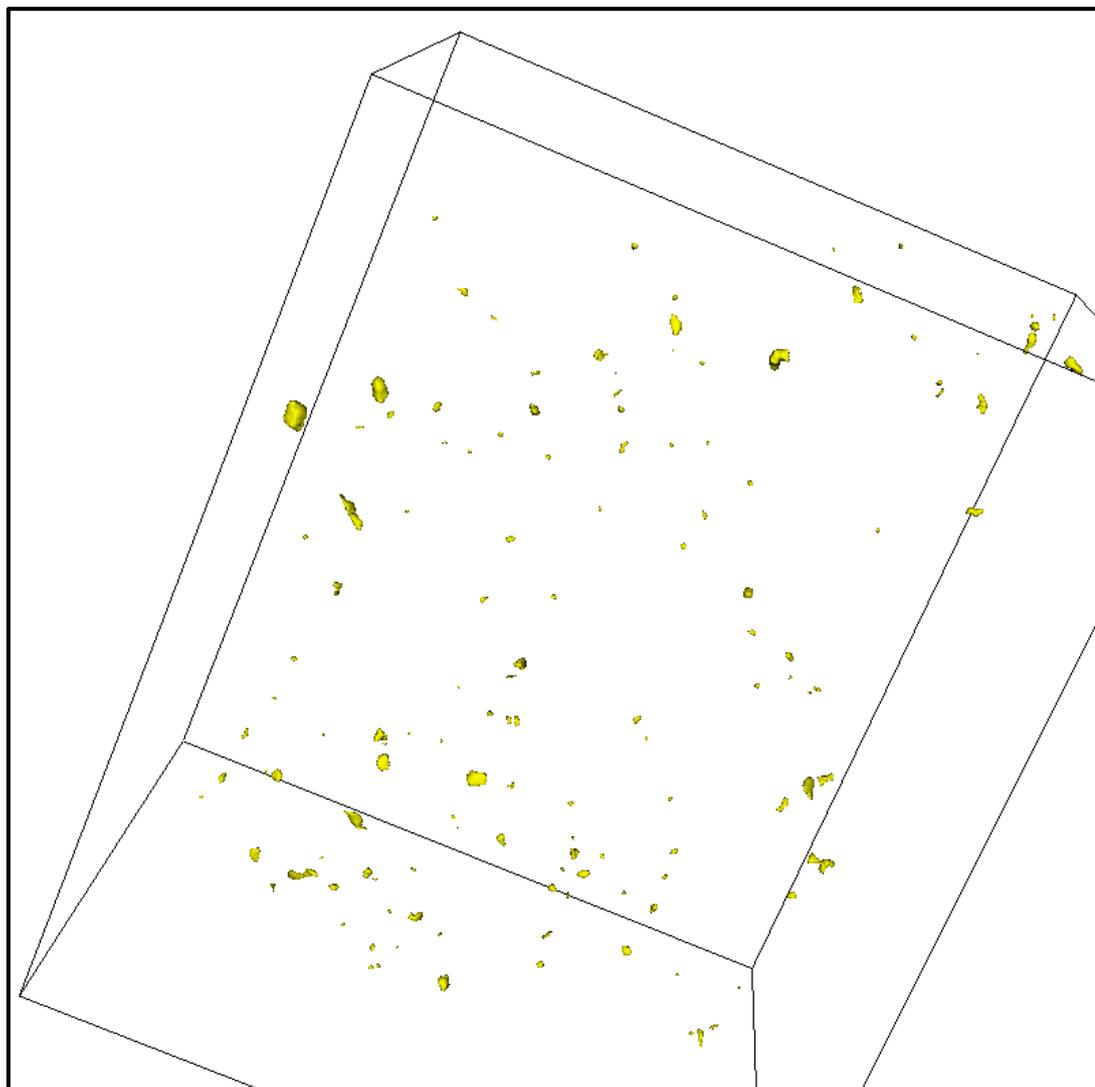


Figure 6-20. Micro CT images of -212/+38 μm gold particles found in the Kanowna Belle Knelson concentrate

The original Kanowna Belle Knelson sample upgraded by MagStream™ contained was concentrated 2.7 times into a +6 SG fraction for tomography. The small concentration effort produced several hundred gold particles for Micro CT analysis, an amount far more than the twelve or so free gold particles identified in the

same sample by QEMSCAN. The particles yield a calculated average sphericity of 0.78 and an average volumetric shape factor of 0.430.

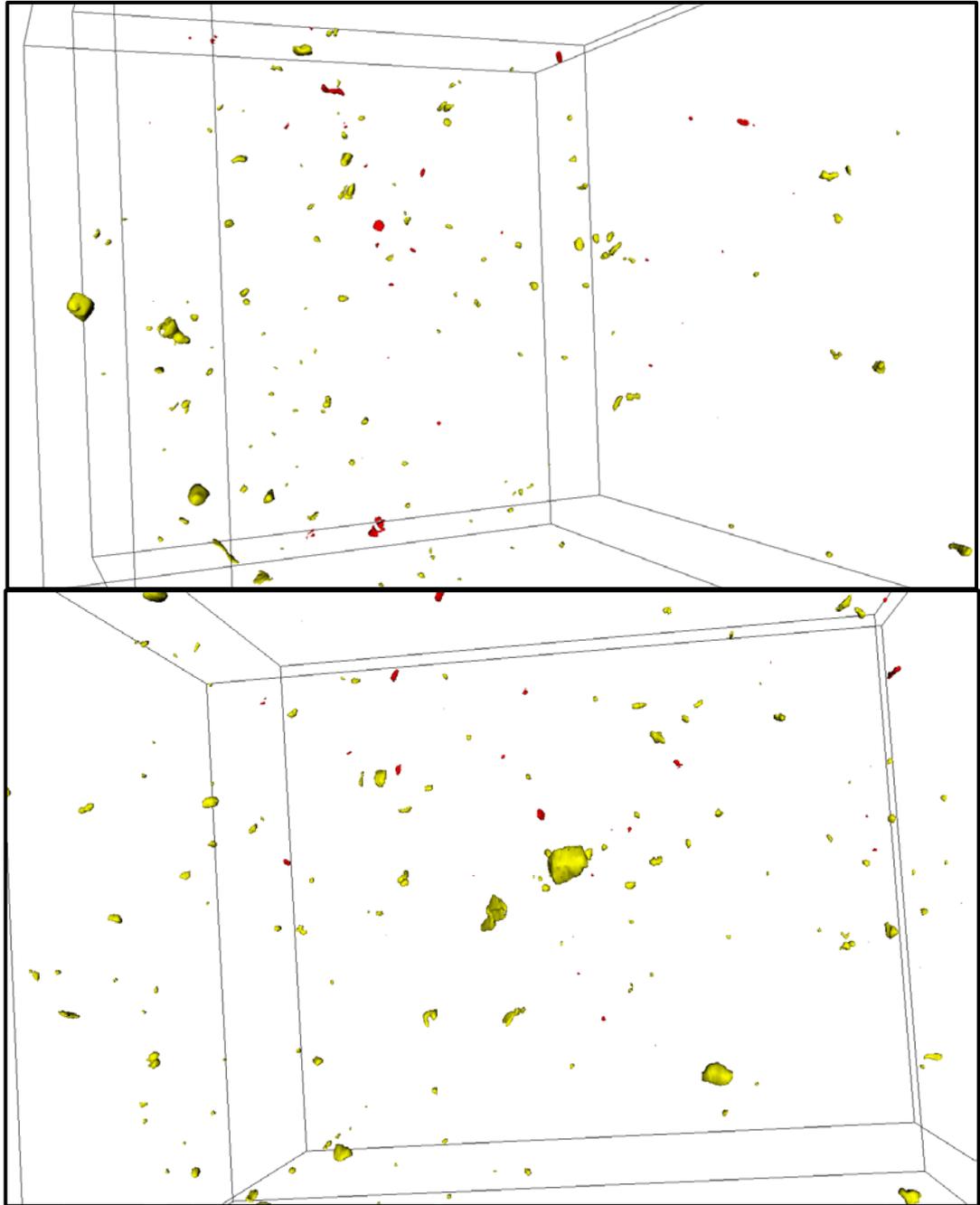


Figure 6-21. Micro CT images of -212/+38 μm gold particles found in the Kanowna Belle flash flotation (red) and Knelson (gold) concentrates

The sphericity factors generated by for the Kanowna Belle Knelson and flash flotation concentrate are identical and more spherical, on average, than particles from the other sites. The 3D shape is more closely described as a cone or a prism ($x, x, 2x$). The average volumetric shape factors for the gold particles in the BCC and flash flotation concentrates, 0.430 and 0.425 respectively, also suggest these particles are more spherical in nature than the others examined in this testwork. These results demonstrate there is less gold particle variation between the flash flotation and BCC concentrates at Kanowna Belle in comparison to Tongon, and particularly, Telfer.

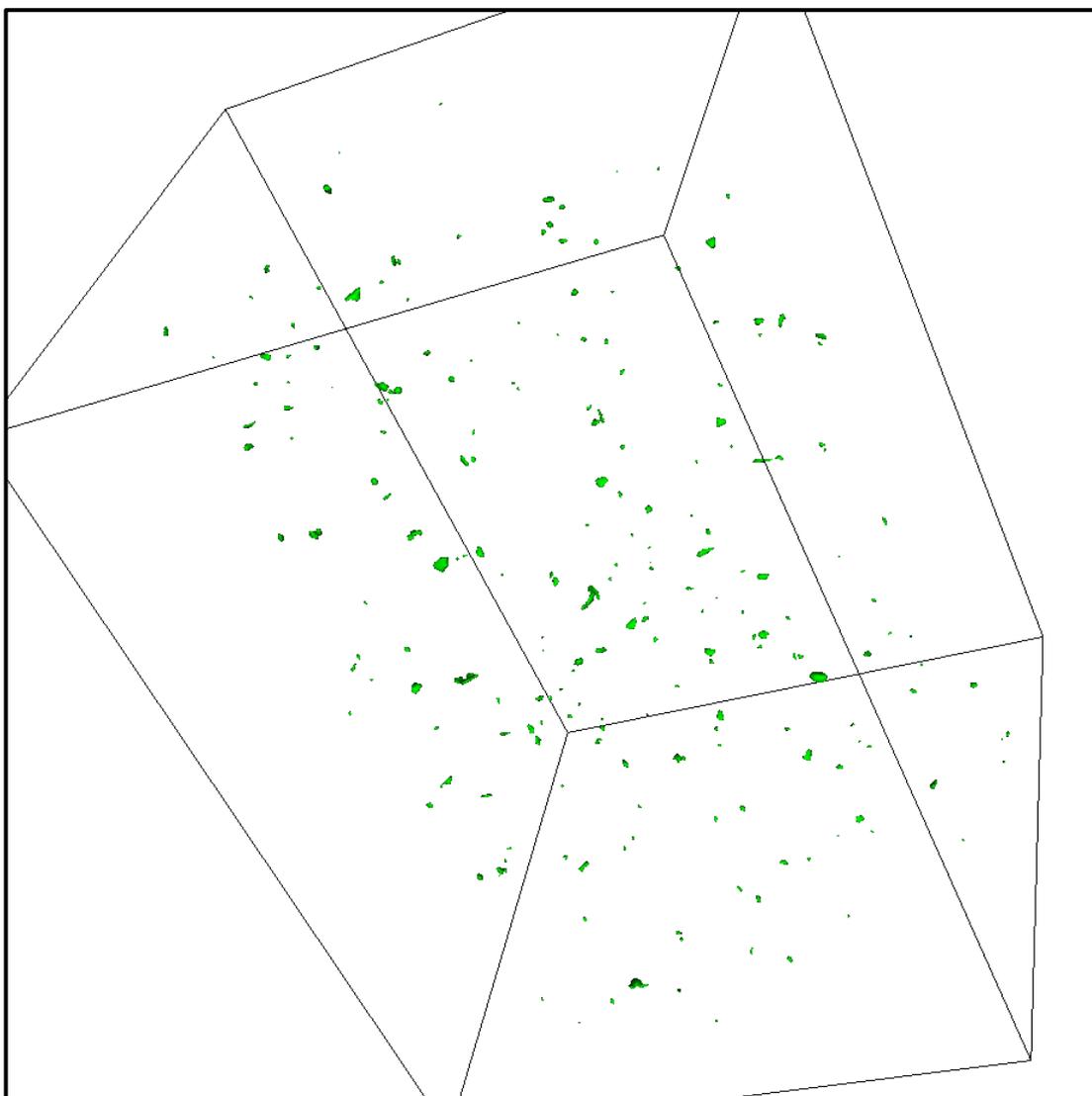


Figure 6-22. Micro CT images of -212/+38 μm gold particles found in the Telfer flash flotation concentrate

The Telfer flash flotation sample was upgraded 9.4 times by MagStream™ to create the +6 SG fraction. The concentration provided almost 350 gold particles for analysis by Micro CT. The measured particles had a calculated sphericity of 0.760 and a volumetric shape factor of 0.405, on average.

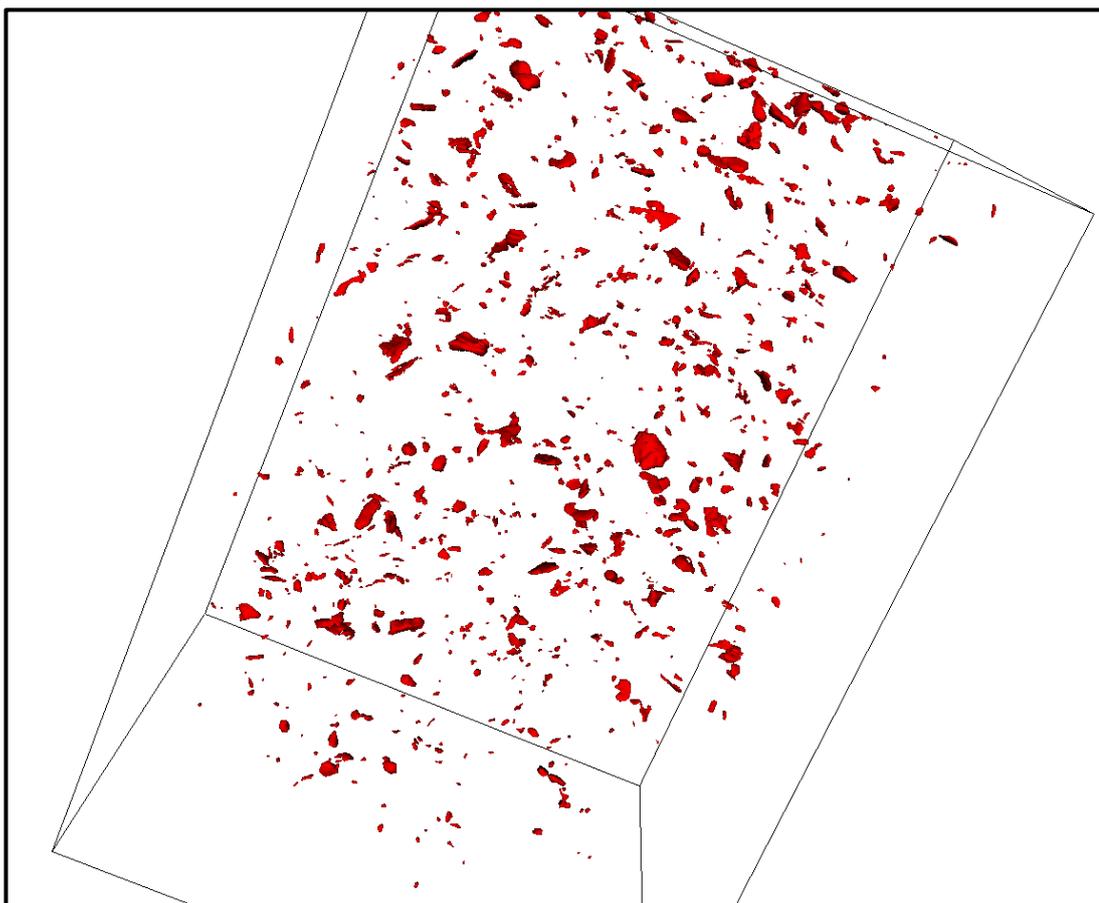


Figure 6-23. Micro CT images of -212/+38 μm gold particles found in the Telfer Falcon concentrate

The Falcon concentrate sample from the Telfer flash flotation circuit was upgraded 4.6 times by MagStream™ to create the +6 SG fraction. The concentration provided almost 4,500 gold particles for analysis by Micro CT. On average, the measured particles had a calculated sphericity of 0.725 and a volumetric shape factor of 0.390.

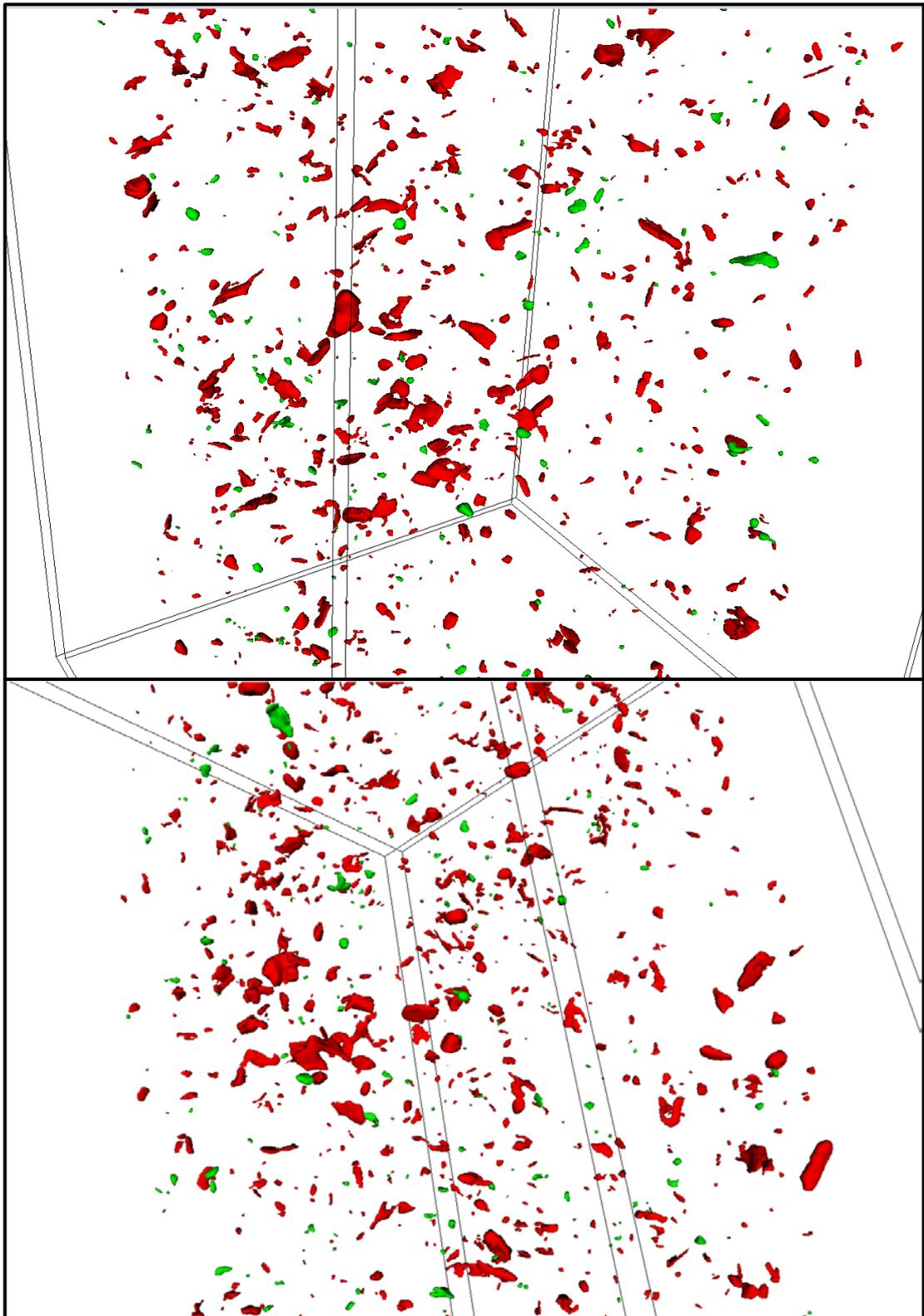


Figure 6-24. Micro CT images of -212/+38 μm gold particles found in the Telfer flash flotation (green) and Falcon (red) concentrates

The sphericity factors generated for the Telfer Falcon and flash flotation show more deviation from each other, on average, than particles from the other sites. The average sphericity factors for the gold particles in the BCC and flash flotation concentrates, 0.725 and 0.760 respectively, demonstrate the deviation in shape and also suggest the BCC concentrate contains particles which are more flat than those of the flash flotation concentrate. This is surprising and contradictory to the 2D circularity analysis conducted in Section 6.2.4 and anecdotal evidence offered in much of the literature. The 3D shape characterisations suggest the free gold particles can be described as a prism (x, 2x, 2x) in the case of flash flotation or prism (x, 2x, 3x) for BCCs.

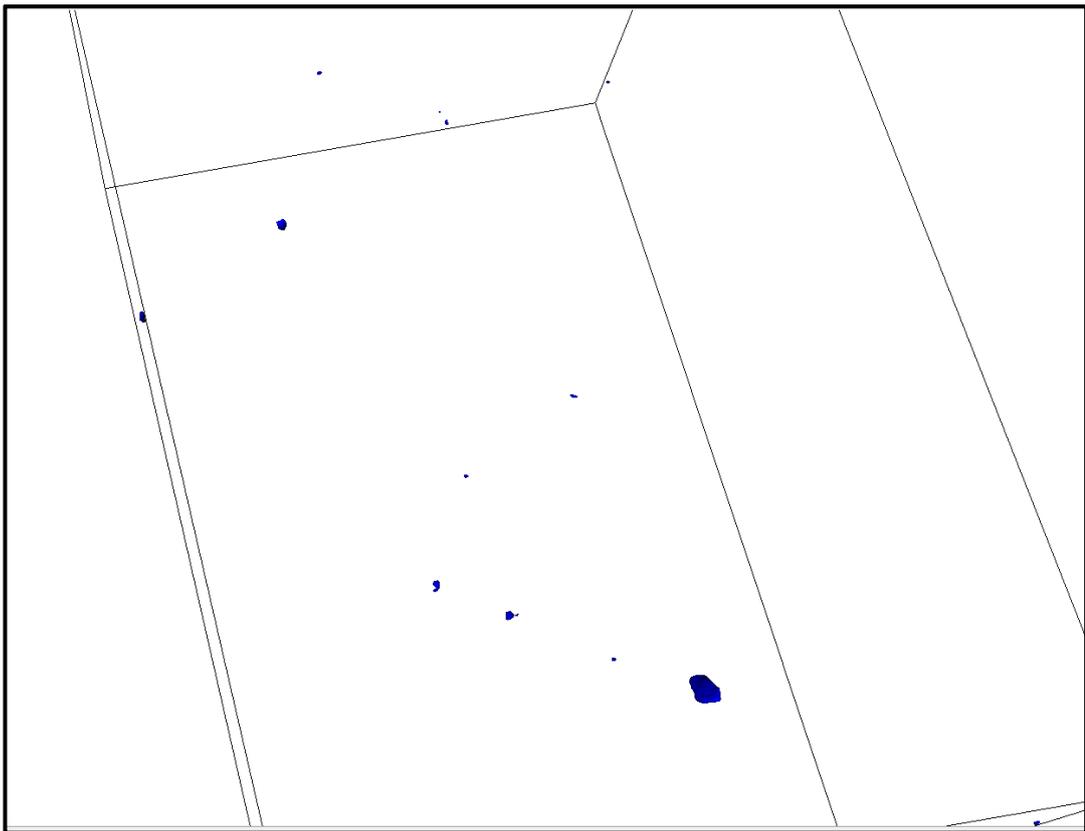


Figure 6-25. Micro CT images of -212/+38 μm gold particles found in the Tongon flash flotation concentrate

The Tongon flash flotation sample was upgraded only by a factor of two by MagStream™ to create the +6 SG fraction. The concentration provided only 24 gold particles for analysis by Micro CT. The average measured particles had a calculated sphericity of 0.745 and a volumetric shape factor of 0.385.

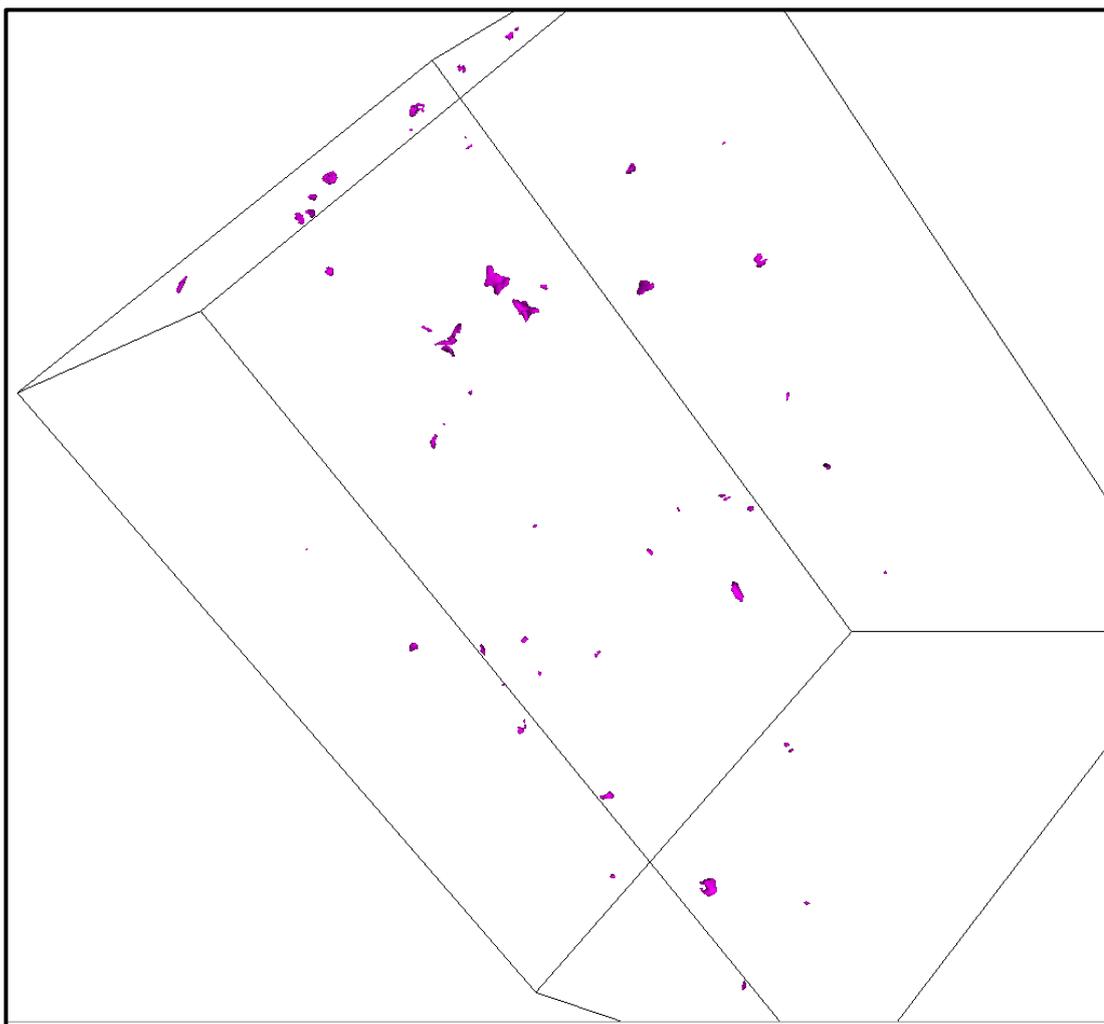


Figure 6-26. Micro CT images of -212/+38 μm gold particles found in the Tongon Knelson concentrate

The Tongon Knelson sample was upgraded 3.2 times by MagStream™ to create the +6 SG fraction. The concentration provided only 180 gold particles for analysis by Micro CT which is far fewer than the BCCs at the two other sites. Particles had an average calculated sphericity of 0.740 and a volumetric shape factor of 0.395.

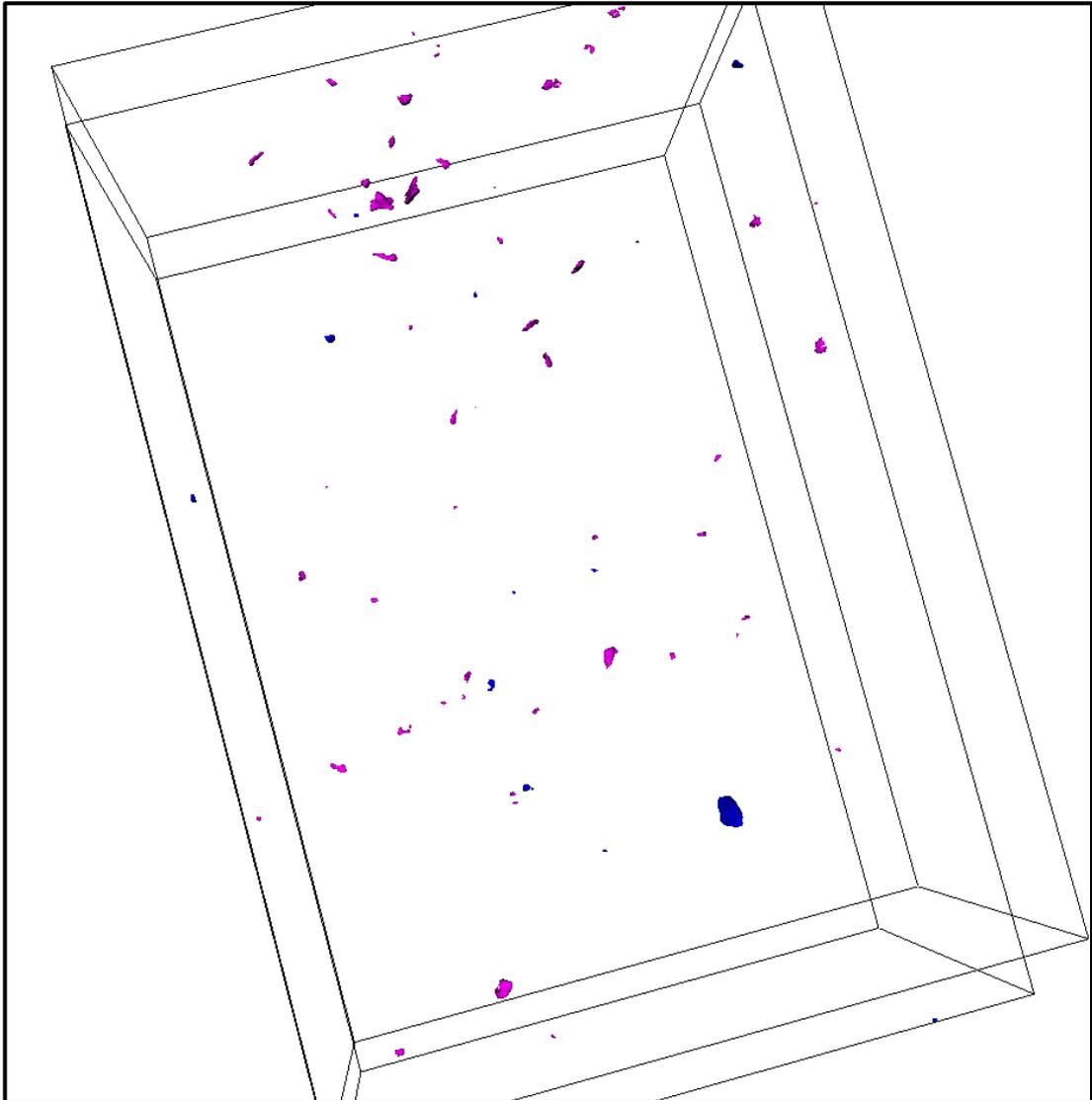


Figure 6-27. Micro CT images of -212/+38 μm gold particles found in the Tongon flash flotation (blue) Knelson (pink) concentrates

The sphericity factors generated for the Tongon Knelson and flash flotation concentrate are quite similar to each other and less spherical, on average, than particles from the other sites. The shape is more closely described a prism ($x, 2x, 2x$) or ($x, 2x, 3x$). The volumetric shape factors for the gold particles in the BCC and flash flotation concentrates, 0.395 and 0.385 respectively, also suggest these particles are less spherical in nature than the other sites examined in this testwork. The results suggest there is little variation in gold particle between the flash flotation and BCC concentrates at Tongon, as can be determined with such a small sample size.

6.3 Summary

This chapter has examined the recovery behaviour of free gold in an industrial setting that has gravity and flash flotation operating in parallel, with an emphasis on the influence of size and shape. This chapter has also considered the accuracy of shape characterisations by existing techniques for the quantification of free gold shape by comparing two and three dimensional (2D and 3D) methods and has identified the limitations of these applications.

The gravity concentrators at all sites in this study have been shown to recover particles below $-212\ \mu\text{m}$ and even in the $-38\ \mu\text{m}$ fraction. This is of interest because these size fractions were originally identified as the zone of competition with flash flotation and the zone for preferred flash flotation recovery, respectively. A 2D QEMSCAN examination of particle size distribution within the +6 SG fraction of the intermediate ($-212/+38\ \mu\text{m}$) size class of the Telfer flash flotation and BCC concentrate was performed. Results reveal that, within the intermediate size class, preferential free gold recovery based on sized is not likely given the following observations:

- There is no significant size difference between gangue and free gold particles found in either recovery unit.
- The bulk flash flotation concentrate is finer within the $-212/+38$ fraction in comparison to the BCC concentrate.

Stereological measurements were also evaluated using images provided by QEMSCAN of the free gold and bulk material in the Telfer concentrates. The circularity of free gold and the bulk sample were calculated and data suggest the free gold particles are less circular than the particles in the bulk. The 2D measurements also determine the free gold in the BCC (Falcon) at Telfer to be more circular than the free gold particles in the flash flotation concentrate.

In contrast, the sphericity measurements calculated from 3D data produced by Micro CT determined that the Telfer BCC units were actually preferentially

recovering flatter particles while, on average, the flash flotation concentrate contains free gold which is more spherical.

This research has demonstrated that the techniques commonly used today to quantify shape descriptions from 2D data are insufficient for effectively describing the 3D shape of irregular mineral particles, specifically malleable metals like gold and especially when they occur in low concentrations. The inability to accurately describe the shape of a free gold particle in the concentrate samples by either 2D or 3D methods is limited by both method and concentration factors which ultimately contribute to the inability to accurately quantify and subsequently differentiate free gold particles from each other.

CHAPTER 7. CONCLUSIONS

The objectives of this thesis were to:

1. Develop a robust and repeatable bench scale flash flotation test (the Free Gold Flash Flotation Test) to determine the maximum free gold recovery. The free gold particles which are recovered in this test represent the ultimate FRFG content. The method will:
 - a. Be repeatable,
 - b. Distinguish free gold from gold in sulfide carriers,
 - c. Determine whether or not the test can be conducted on dry plant samples, and
 - d. Provide conditions which maximise FRFG recovery across the possible range of physical and chemical factors known to affect recovery of free gold in flotation. This type of information previously existed in an anecdotal form but will now be demonstrated with the laboratory testwork.
2. Investigate the response of free gold of differing genesis in key size classes (coarse, intermediate and fine) to changes in collector dosage.
3. Determine the recovery behaviour of free gold in an industrial setting with gravity and flash flotation operating in parallel, with an emphasis on the influence of size and shape.
4. Evaluate the accuracy of stereological measurements from existing techniques for the quantification of free gold shape by comparing two and three dimensional (2D and 3D) methods and identifying the limitations of these applications.

The conclusions made in light of achieving these objectives and future recommendations are fully outlined in this chapter.

7.1 Development of a Laboratory Test to Quantify the Ultimate Flash Recoverable Free Gold (FRFG) Content of an Ore

An evaluation of a number of flotation techniques commonly used at mine sites and at commercial laboratories was used to develop a repeatable flash flotation method and, for the first time, batch flash flotation tests were conducted on a gravity concentrate to determine the effect of operational conditions and reagent additions on the recovery of free gold using the Free Gold Flash Flotation test. As presented in Chapter 4, the free gold recovered by the new flash flotation test was defined as Flash Recoverable Free Gold or FRFG. The method for determination of the FRFG content of either a brownfield or greenfield ore by means of the Free Gold Flash Flotation test has been provided. Using this method, the FRFG laboratory recoveries demonstrated a repeatability of $\pm 0.45\%$ (average) for mass pull while gold recovery was less precise at $\pm 4.63\%$ (average).

The Flash Flotation for Free Gold test was then applied to characterise the flash flotation behaviour of free gold in a synthetic ore containing a BCC concentrate as a function of changes made in the operational and reagent variables. The testwork indicated:

- The effects of airflow and frother, at the tested levels, appeared to have no significant impact upon free gold recovery whether evaluated independently or in conjunction with the other four tested factors. Although these factors have been shown to be of importance in the plant (Kallioinen and Heiskanen, 1993; Ross, 1990), their lack of influence at the tested levels in the laboratory flotation set-up suggests airflow and frother levels were sufficient for recovery of free gold.
- The remaining factors (agitation, collector and sulfide addition) exhibited variable responses when evaluated independently or in combinations.
 - As with industrial flash flotation units, attention must be paid in the laboratory to ensure adequate agitation for mixing in order to prevent

sanding and properly integrate the reagents with the pulp, particularly in cases of short retention time.

- Collector dosage has also been shown to be of great importance in recovery of gold particles as an independent variable (additional testwork was conducted in Chapter 5 to explore this relationship further).
- Interestingly, the addition of pyrite as a source of non-gold hosting sulfide material made no contribution by increasing mass pull or kinetics nor did it decrease free gold recovery (as expected through crowding) at the levels tested.
- In contradiction to some of the referenced literature, the use of copper sulfate as an activator appeared deleterious for the recovery of free gold in this testwork. This however, has been the only study evaluating the activation of free gold by copper sulfate in a synthetic ore with BCC concentrate as the gold source so differing results may be due to added complexities in other systems, or, in particular, at a plant where the reagent is noted to increase froth stability.
- The presence of silver (in the form of electrum) was demonstrated to have an influence on improving kinetic rates as well as recoveries.
- Three kinetic models (single component, fixed three component and three component) were evaluated for this testwork with the three component model demonstrating the best fit experiments with low error values. All three models demonstrated a relatively equal fit when errors were large, despite increased model complexity.

7.2 Effect of Collector Dosage and Free Gold Genesis on per Size Response

Further laboratory testwork using the Flash Flotation for Free Gold test to study the effect of size, residence time and natural hydrophobicity in the flotation of BCC and pure gold particles was described in Chapter 5. The work to characterise the behaviour of FRFG in the two synthetic systems with ore of varying genesis

(pure gold powder particles and free gold from a BCC concentrate of mixed origin) demonstrated that:

- Overall, superior recovery was noted for the synthetic Au powder particles by collectorless flotation when compared to the GRG concentrate free gold particles of similar size fractions. This is because the sulfide and alloying components of the GRG concentrate influence the surface chemistry of the GRG differently than pure gold which, combined with surface alterations due to milling and as a result of ions in the slurry, decrease the natural hydrophobicity of GRG as compared to pure gold.
- This work also demonstrated that the recovery of FRFG can be enhanced with increased use of PAX, as clearly shown in the overall recovery data.
 - Interestingly, the Au powder particles were better recovered by collectorless flotation than the GRG concentrate as would be expected from an untarnished particle (Chryssoulis et al., 2003) but, unlike the GRG concentrate, they also demonstrated decreased overall recovery at higher levels of PAX addition. This is most likely explained by over dosage of collector causing multi layers of collector to form on particles which reduce the proportion of nonpolar groups oriented towards the slurry.
 - As predicted by Trahar (1981), higher recoveries of coarse particles required additions of PAX, which was confirmed in this testwork for both GRG concentrate and the Au powder particles.
 - Although industrial flash flotation units experience better hydrodynamic conditions and achieve higher coarse particle recoveries than laboratory cells (MacKinnon et al., 2003), the +212 μm GRG particles in this testwork are unlikely targets for recovery in industrial flash flotation as they primarily display slow kinetic rates. The insufficient recovery of coarse gold particles in flash flotation laboratory testing agrees with the findings of MacKinnon (2002) and Newcombe et al. (2012b) regarding coarse particle sulfide flash flotation trends.

- The intermediate sized Au powder and GRG concentrate particles were recovered similarly in the laboratory flotation test with the collector PAX, although the Au powder particles displayed superior potential for collectorless flotation in this size range (as well as the other two size ranges) compared to the GRG concentrate. The superior inherent floatability of the unmilled Au powder particles in collectorless flotation suggested a possible deleterious effect of milling on the natural hydrophobicity of FRFG such as the imbedding of gangue or changes in shape as gold is progressively comminuted. Such factors have less importance with brittle, isometric particles such as sulfides and gangue silicates. This further emphasises the importance in targeting the removal of free gold as early in processing as possible.
- The fine Au powder particles were better recovered for all experiments than the GRG concentrate under corresponding conditions. Again, this demonstrates the deleterious effect of milling on free gold's natural hydrophobicity. The improved recovery of fine GRG with increased residence time and PAX addition gives evidence for the need for conventional flotation circuits to recover not only sulfides but free gold as well to achieve acceptable plant recoveries.
- Kinetic evaluations using the same models discussed in Chapter 4 indicate intermediate and fine gold particles from both sources were either recovered in the first 30 seconds or reported to tails.
 - As would be expected, the kinetic data from this testwork suggest that fine and intermediate, free gold particles will float faster than comparable sized sulfide and gangue materials, in a comparison to data published in other studies (Kallioinen and Niitti, 1985). Satisfactory kinetics coupled with reasonable flash flotation period recoveries with an addition of PAX, suggest both intermediate and fine GRG particles are appropriate targets for a target concentrate (composition, grade) in industrial flash flotation situations.
 - The increased ultimate recoveries of free gold particles compared to flash flotation recovery values demonstrate that improved recovery of FRFG

particles necessitates additional collector and residence time, similar to the conditions found in conventional flotation circuits.

7.3 Characterisation of Free Gold Concentrated in Flash Flotation and Gravity Concentrator Units at Industrial Scale

Chapter 6 examined the recovery behaviour of free gold in industrial settings that have gravity recovery and flash flotation operating in parallel, with an emphasis on the influence of size and shape. The chapter also considered the accuracy of shape characterisations by existing techniques for the quantification of free gold shape by comparing two and three dimensional (2D and 3D) methods and has identified the limitations of these applications.

In this study, the concentrate from BCC units, which are known to produce a higher grade concentrate than a flash flotation unit, offered more free gold particles which provided a more statistically sound sample. Interestingly, the gravity concentrators at all sites (Tongon, Telfer and Kanowna Belle) demonstrated a surprising efficiency in recovering particles below $-212\ \mu\text{m}$ and even in the $-38\ \mu\text{m}$ fraction, which were originally identified as areas of competition with flash flotation units and the flash flotation preferred size fraction, respectively.

Flash flotation units are often beset by operational and mechanical complications, with all three sample sites struggling to pull an acceptable concentrate (in terms of either mass, grade or both) at the time of their respective survey. Although the Telfer flash flotation units had been classified as operating below par at the time of the survey, its ore has a greater free milling component than the other sites, yielding more particles for characterisation. The other sites, Kanowna Belle and Tongon, offered fewer particles for characterisation. Operation and amenability issues make it harder to analyse the few free gold particles contained in relatively low grade concentrates in order to obtain a sufficient amount of material to statistically quantify the types of particles recovered. In general, of the gold particles studied in the flash flotation concentrates, an overwhelming majority tend to be associated with sulfides which may be attributed to the mineralogy (i.e. little to no

coarse or intermediate free gold) and operational strategy more than the floatability of individual gold particles.

A 2D examination of particle size distribution was performed by QEMSCAN on the +6 SG fraction of the intermediate (-212/+38 μm) size class of the Telfer flash flotation and BCC (the site was selected for its superior free gold content). Results reveal that within the intermediate size class, preferential free gold recovery based on size is not likely given the following observations:

- There is no significant size difference between gangue and free gold particles found in either recovery unit.
- The bulk flash flotation concentrate is finer within the -212/+38 fraction in comparison to the BCC concentrate.

Stereological measurements were also evaluated using images provided by QEMSCAN of the free gold and bulk material in the Telfer concentrates. The circularity of free gold and the bulk sample were calculated and data suggests the free gold particles are less spherical than the particles in the bulk. The 2D measurements also determined the free gold in the BCC (Falcon) concentrate at Telfer to be more circular than the free gold particles in the flash flotation concentrate.

In contrast, the sphericity measurements calculated from 3D data produced by Micro CT determined that the Telfer BCC units were preferentially recovering flatter particles while, on average, the flash flotation concentrate contained free gold which is more spherical.

This research has demonstrated that the techniques commonly used today to quantify shape descriptions from 2D and 3D data are insufficient for effectively describing the shape of irregular mineral particles, specifically malleable metals like gold and especially when they occur in low concentrations. The inability to accurately describe the shape of a free gold particle in the concentrate samples

contributes to an inability to accurately quantify and subsequently differentiate them from each other.

Previous studies about the shape effect on flotation of particles of a siliceous nature suggest flat, elongated particles are recovered better and faster than round and smooth particles (Drzymala and Vigdergauz, 2000; Rahimi et al., 2012) suggesting particles found in a flash flotation concentrate could be expected to fit this description. While the 2D results support that concept, the Micro CT and QEMSCAN analyses performed on the flash flotation and BCC concentrates were in contradiction. This research has established the following limitations of stereology and shape determinations from 2D data:

- The QEMSCAN data produced circularity measurements for gold containing particles that agree with the previous findings, suggesting that flotation would preferentially recover flatter particles than gravity devices. However, the previous studies were primarily conducted on silicate mineral samples and this research demonstrated no difference in the bulk material (mostly silicates) between the flash flotation and gravity concentrates as would have been expected, rather the difference was noted in the particles identified as being primarily composed of gold.
 - It is likely that QEMSCAN overestimated the number of “free gold” particles in the flash flotation cases, which means that 2D shape calculations were performed on gold in carriers as well as free gold particles and ultimately, the circularity calculations are not representative of just free gold particles. This is a function of the type of measurement used for analysis, the rare element scan, and is evident in the QEMSCAN images given in Section 6.2.
- Another inability to define and compare shapes of gold particles lies in the fact that many different techniques exist and are commonly used today to quantify shape from 2D with little ability to make comparisons between the 2D measurements let alone the 3D shape quantifications.

- It was determined that descriptions from Micro CT data are also insufficient in effectively describing the shape of irregular mineral particles, specifically malleable metals like gold. While the 3D measurements should offer more gold particles for shape characterisations based on the larger volume of material being analysed in comparison to the 2D QEMSCAN measurement, no liberation or gangue material associations can be made from the Micro CT figures given in Section 6.2.
 - Therefore, while the shapes of free gold are more accurately visualised in the 3D data set, there is no confirmation available that the particles are “free gold”.
- There is a severe inability to accurately describe the shape of free gold particles in the concentrate samples with the techniques explored in this study which has contributed to an inability to accurately quantify and subsequently differentiate them from each other in both the 2D and 3D data sets. The use of other, more accurate, estimations for the quantification of gold particles (Lin and Miller, 2005) was investigated but the methods are not commonly used nor have they been applied to gold particles in any publications at the time of this thesis.
- Other reasons for the deviation in floatable shape preference between silicates and gold could be differences in density, surface area and sensitivity to pulp chemistry. Higher density means the gold particles are more likely to disengage after attachment due to bubble particle interactions and, in the case of flat particles, a large contact angle. The limited data produced in this study supports the suggestion that it is likely that the small rounded edge of a flat gold particle is attached to the underside of a bubble rather than the particle’s larger flat surface (Dunne, 2014). Such types of attachment require less force to separate (Drzymala and Vigdergauz, 2000) which is particularly true in high density flash flotation slurries (MacKinnon, 2002). This proposed mechanism for parallel presentation of a flat gold particle relative to the direction of pulp flow (Figure 2-11) at a rate higher than creeping motion can be expected as it minimises drag (Rhodes, 2008).

- Askoy and Yarat (1989) proposed that native gold flakes have highly roughened, flat surfaces and that greater roughness is responsible for decreased bubble attachment and floatability. However, Allan and Woodcock (2001) claim the opposite it is true; rather that flat particles present a larger surface area for collector and bubble attachment and settle more slowly offering greater floatability than cubic particles of similar composition. Depending on the method of shape characterisation used in this study, both groups of researchers are supported; i.e. the 2D data support the findings of Allan and Woodcock while the 3D data from this research would appear to support the findings of Askoy and Yarat.

7.4 Recommendations for Future Work

This research has provided a basis for characterising the Flash Recoverable Free Gold (FRFG) content of an ore by use of the Flash Flotation for Free Gold test, as well as preliminary understanding on the effect of collector and free gold genesis will have on recovery. This is by no means an exhaustive study and some recommendations for further research in this area include:

- Application of the Flash Flotation for Free Gold test to determine the FRFG content of various ores.
- Comparisons of the laboratory predicted FRFG content to actual plant recoveries for the basis of a free gold flash flotation model and, eventually, used to evaluate the performance of industrial operations.
- Determination of acceptable methods to quantify shape of malleable particles.
 - To validate the 3D calculations made for gold volume by the Micro CT measurements by reconciliation of gold grade calculations from volume data with fire assay results (a similar study could also be performed with the 2D QEMSCAN data). Differences could then be evaluated and possibly attributed to inadequate voxel resolution, poor fit in the models for size/surface area/ volume calculations and undetected gold content in sulfide matrix.

CHAPTER 8. REFERENCES

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CHAPTER 9. APPENDICES

9.1 Free Gold Flash Flotation Test

9.1.1 Overview

The aim of flash flotation is to quickly recover liberated minerals of interest that would otherwise return to the grinding circuit via the hydrocyclone due to their high specific gravity and be further reduced in size. Flash flotation removes these particles from the milling circuit which prevents overgrinding and loss of recovery.

9.1.2 Procedure

1. Mix reagents prior to testwork, label and use stock solution for up to one week.
2. Add a required mass of BCC concentrate, silica (3 parts Cook's Superfine to 1 part Sibelco 200 #) and pyrite (100 % passing 200 μm) to a clean and dry flash flotation cell. Record masses. Size analyses of materials used are provided in Table 1.A.2. Mass of sample should total 1 kg.
3. Add required volume of tap water to achieved specified pulp density in the flotation vessel containing the dry solid material.
4. Set flotation cell into flotation machine and ensure it is fully engaged before lowering impeller and shaft.
5. After the stator is situated along the bottom of the cell, the shaft can be locked into place.
6. Start agitation at prescribed rate (RPM), using digital control to achieve desired set point.
7. Use a glass or metal rod to check corners for sanding.
8. Record slurry pH.
9. Turn on airflow to fix at mandated set point, turn it off at the ball valve so adjusting of the set point during operation will be minimised.
10. Add required reagents in the following order: collector, then activator, and finally frother.
11. Allow 10 seconds for conditioning before turning on the airflow, starting the timer and commencing testwork.

12. Use specifically designed paddles to scrape froth at 5 second intervals during the sample time. See Table 9-1 for the froth scraping sequence used in this phase of testing.
13. Quickly perform this sample pan change out procedure following the last scrape of the sample (10 seconds elapsed time maximum):
 - a. quickly turn off air at ball valve
 - b. stop timer and reset to 0 seconds
 - c. rinse material on lip of float cell and paddles into sample pan
 - d. rinse material on vessel side walls and impeller shaft into the slurry
 - e. restart air and timer
 - f. change to next sample pan
14. Repeat steps 12 and 13 for duration of test. Pay attention to times required and elapsed time for each sample, as they are varied in the last few samples.
15. Take a final pH reading after collecting all concentrate samples.
16. Use Buchner funnel, filter paper and vacuum flask to remove water from concentrate samples.
17. Use pressure filter and filter paper to remove water from tails sample.
18. Dry all samples overnight in oven set at less than 80 °C to prevent oxidation of sulfides.
19. Record dry mass of each filter paper and sample, as they will be required for the subsequent cyanidation testing.

Table 9-1. Sample collection schedule

Sample #	Sample Duration (s)	Elapsed Time (s)	# of Scrapes
1	30	30	6
2	30	60	6
3	30	90	6
4	30	120	6
5	60	180	12
6	120	300	24
7	180	480	36

Table 9-2. Sizing data for synthetic ore components

% Passing (Cumulative)			
Screen Aperture (μm)	Sibelco SiO₂	Cooks SiO₂	BCC Con
850	100%	100%	x
600	100%	100%	x
425	100%	97%	x
300	100%	74%	x
212	100%	42%	82%
150	100%	27%	65%
106	100%	25%	44%
75	100%	24%	25%
53	83%	18%	18%
38	40%	16%	15%
25	34%	14%	0%
15	0%	0%	x

9.2 Laboratory Intensive Cyanidation Bottle Roll Procedure

9.2.1 Overview

The aim of using a bottle roll cyanidation test is to determine the amount of leachable (free) gold, and in some cases silver, contained in the sample of interest produced from the Free Gold Flash Flotation Test. Leach residues can be subjected to fire assay to determine the remaining gold in the sample.

9.2.2 Principle of the Method

Cyanide dissolves available gold into solution. The solutions can then be assayed with AAS, when in the ppm range, or ICP-MS, when in the ppb range. Bottles are vented to allow for gas transfer, ensuring lack of oxygen does not limit the reaction rate. The slurry and cyanide are agitated by rolling the bottle to maximise kinetics.

9.2.3 Equipment and Reagents

2.5L Winchester reagent bottles

Vented Winchester reagent bottle lids

Portable pH probe and meter

Analytical balance

Graduated cylinder

Top loading balance (capable of up to 6kg)

Drying oven

Bottle rolling apparatus

Buchner funnels (with Filters)

Funnels for solid and liquid additions

Squirt bottle with tap water

Vacuum flask

Sample storage bags

Sample pans

Laboratory notebook

Sodium cyanide (NaCN)

Sodium hydroxide (NaOH)

9.2.4 Procedure

1. Obtain tare masses for all Winchester reagent bottles (without lids) to be used, ensure they are clean and dry.
2. Add one sample to each bottle, include the filter paper. Note individual masses of sample and filter paper.
3. Add about 500ml of tap water to each bottle.
4. Adjust pH to ~10.5 using a sodium hydroxide solution. Agitate and allow bottles to sit for 15 minutes, verify pH measurement.
5. Record mass of bottle, sample and fluids to later determine exact volume of water added.
6. Add ~1.5 g of NaCN.
7. Ensure all lids are tight on the bottles and start bottles rolling. Note this as time T_s .
8. After 24 hours, stop bottles and note this time as F_t .
9. Obtain mass of bottle (no lid) and slurry at time T_f to later determine if significant evaporation occurred.
10. Allow solids in bottles to settle before pouring off a ~50 ml sample for AAS.
11. Vacuum filter remaining slurry.
12. Dry overnight in oven at 80 °C.
13. Obtain dry residue mass and prep for fire assay submission.
14. Filter, laboratory and store the AAS samples until ready for analysis.
15. Repeat steps 9-13 for all samples.

9.3 SEM-EDS Scans of Selected GRG Gold Particles

The following SEM-EDS images depict common shapes and the elemental distributions found in particles of the BCC concentrates.

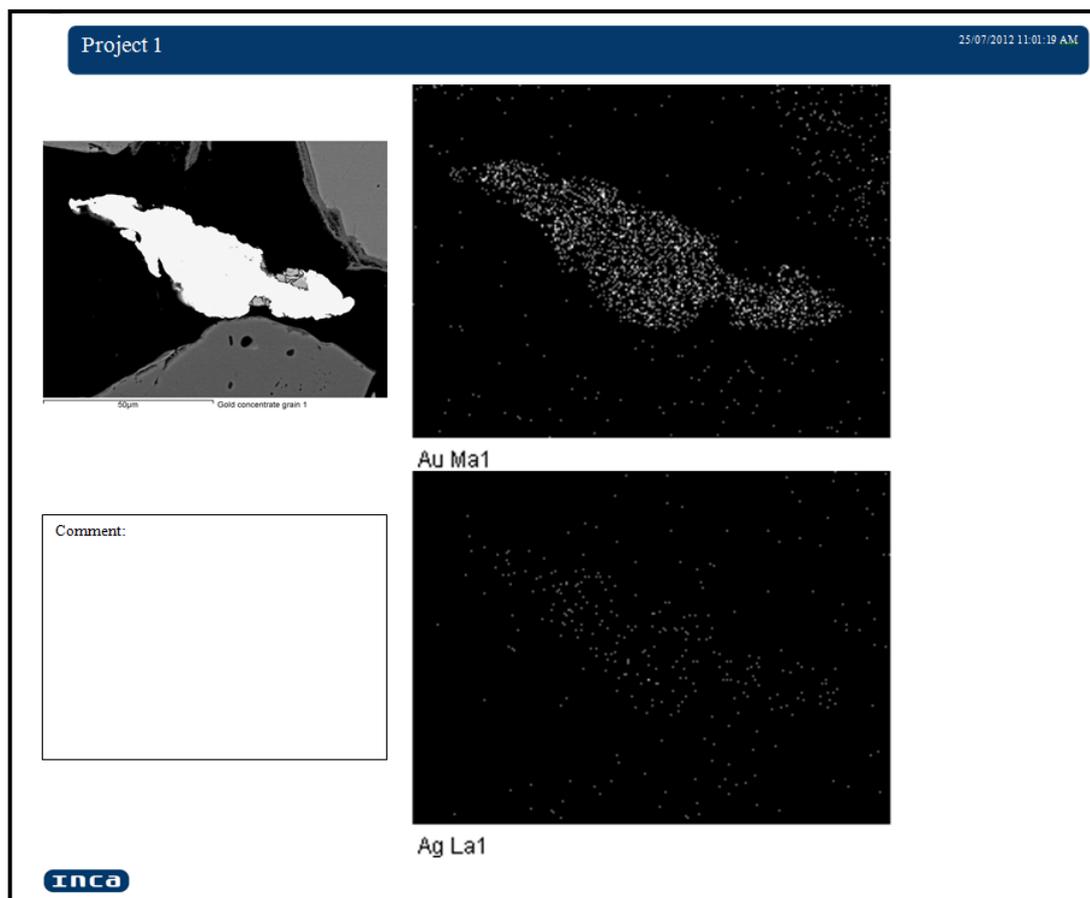


Figure 9-1. SEM-EDS scan mapping elemental gold and silver distribution in a particle of free gold from a BCC concentrate

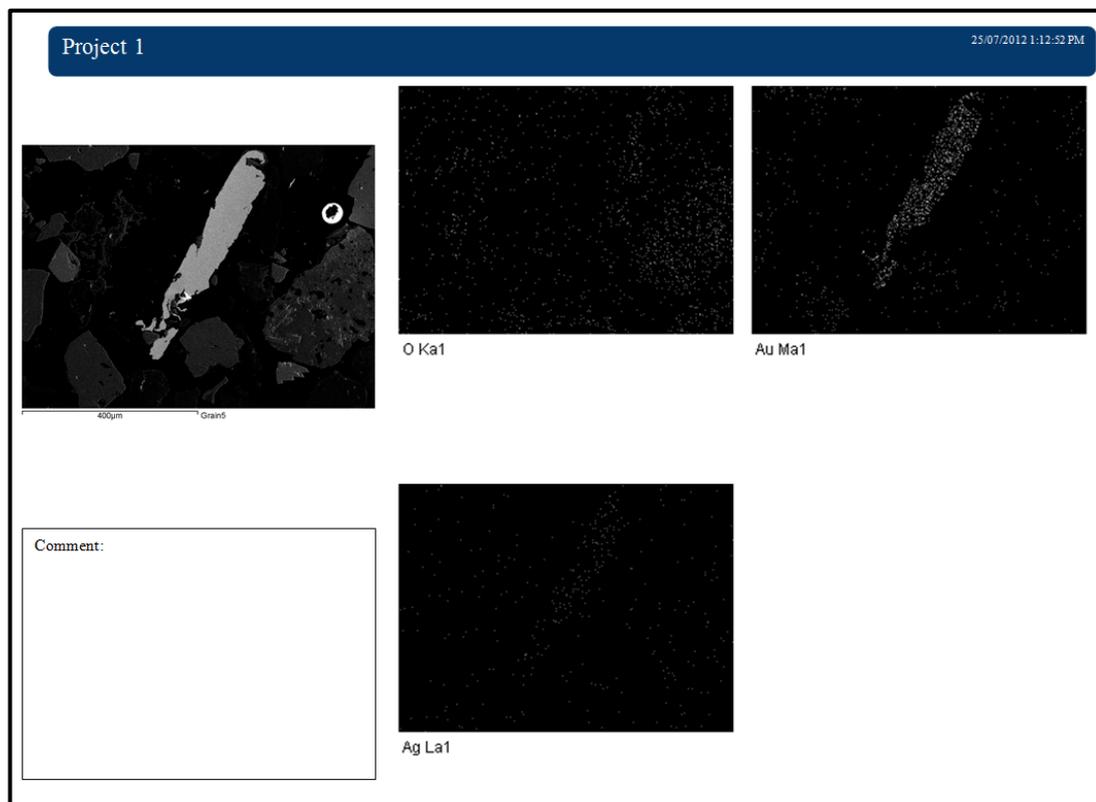


Figure 9-2. SEM-EDS scan mapping elemental distributions in a particle of free gold from a BCC concentrate

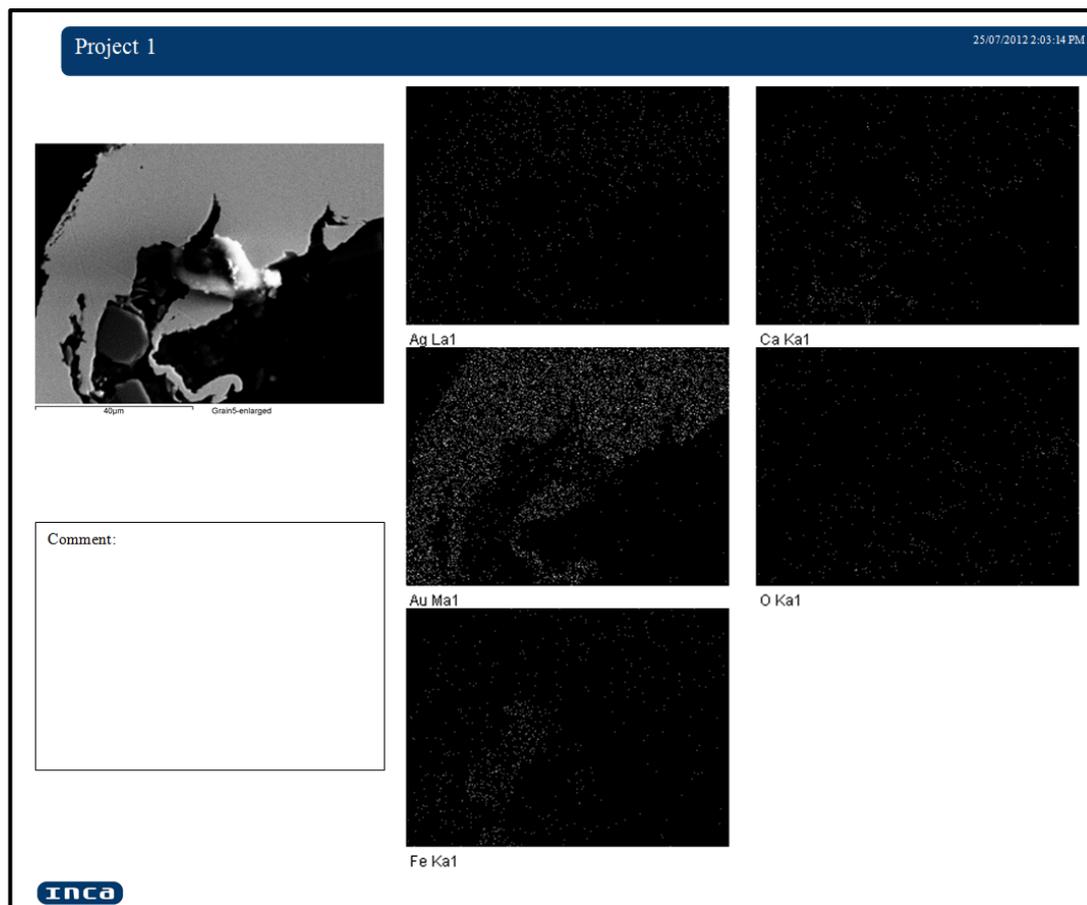


Figure 9-3. SEM-EDS scan mapping elemental distributions in a particle of free gold from a BCC concentrate

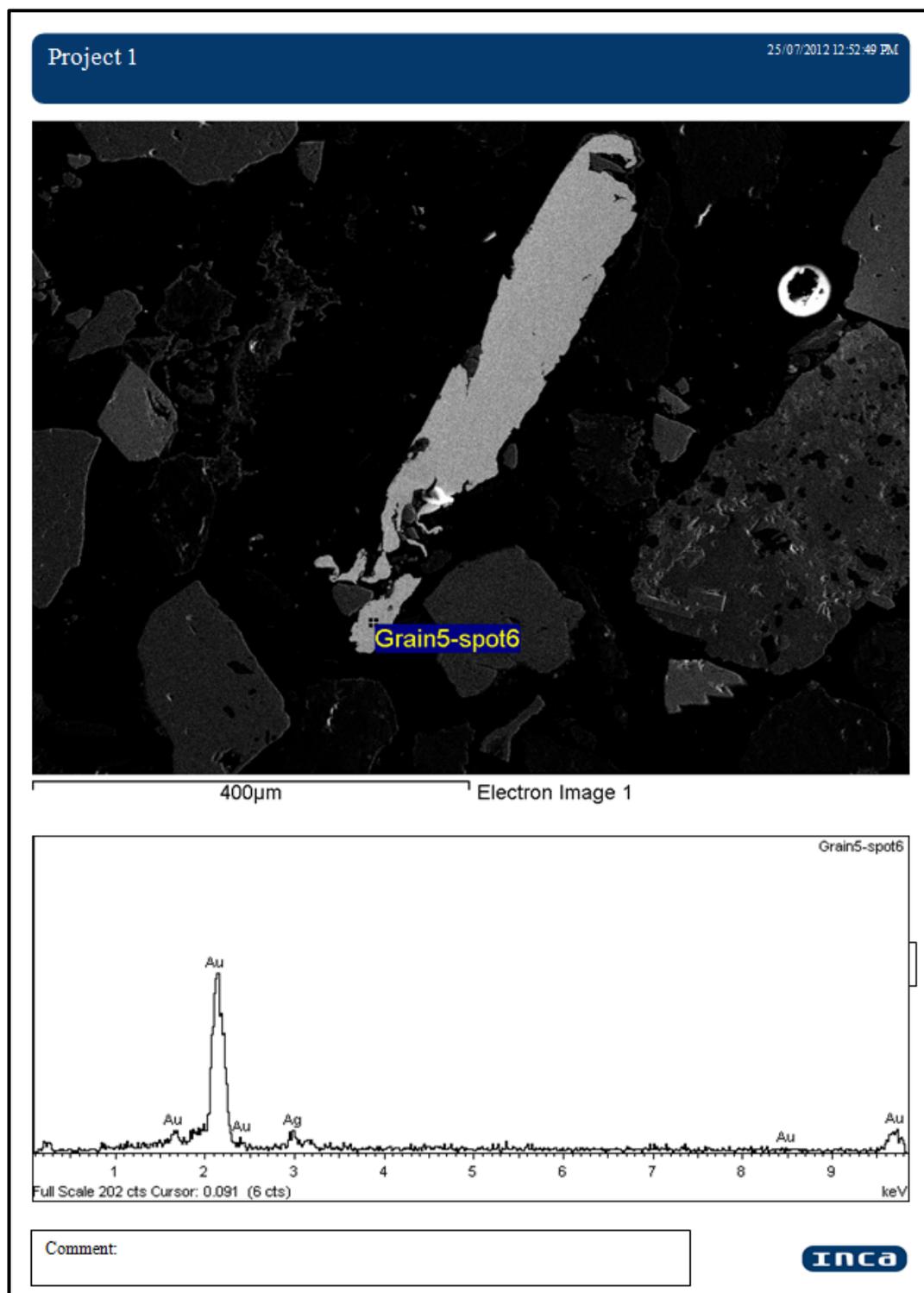


Figure 9-4. SEM-EDS image and spectra demonstrating elemental gold and silver occurrence at a particular spot of a particle of free gold from a BCC concentrate

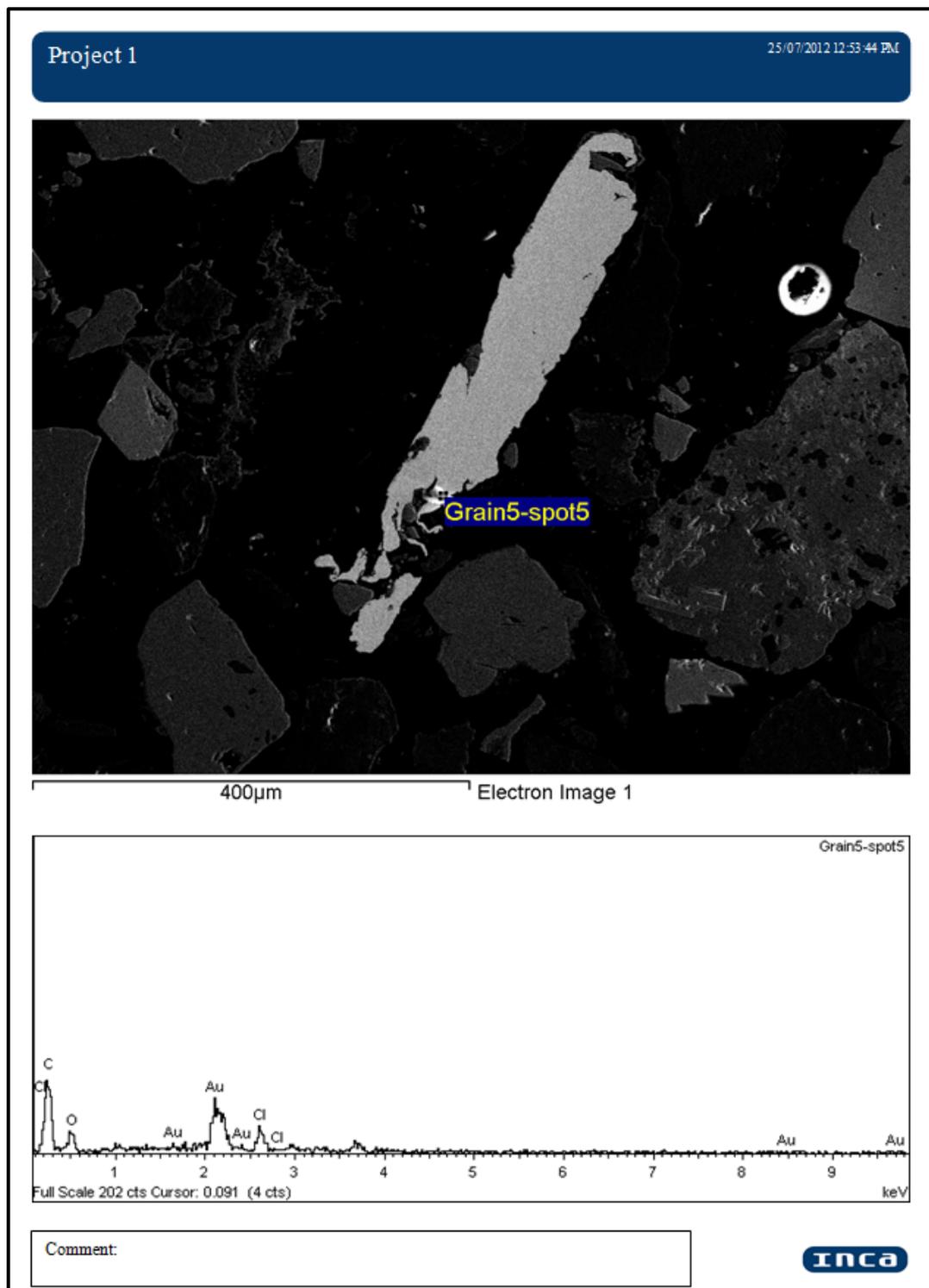


Figure 9-5. SEM-EDS image and spectra demonstrating elemental gold and silver occurrence at a particular spot of a particle of free gold from a BCC concentrate

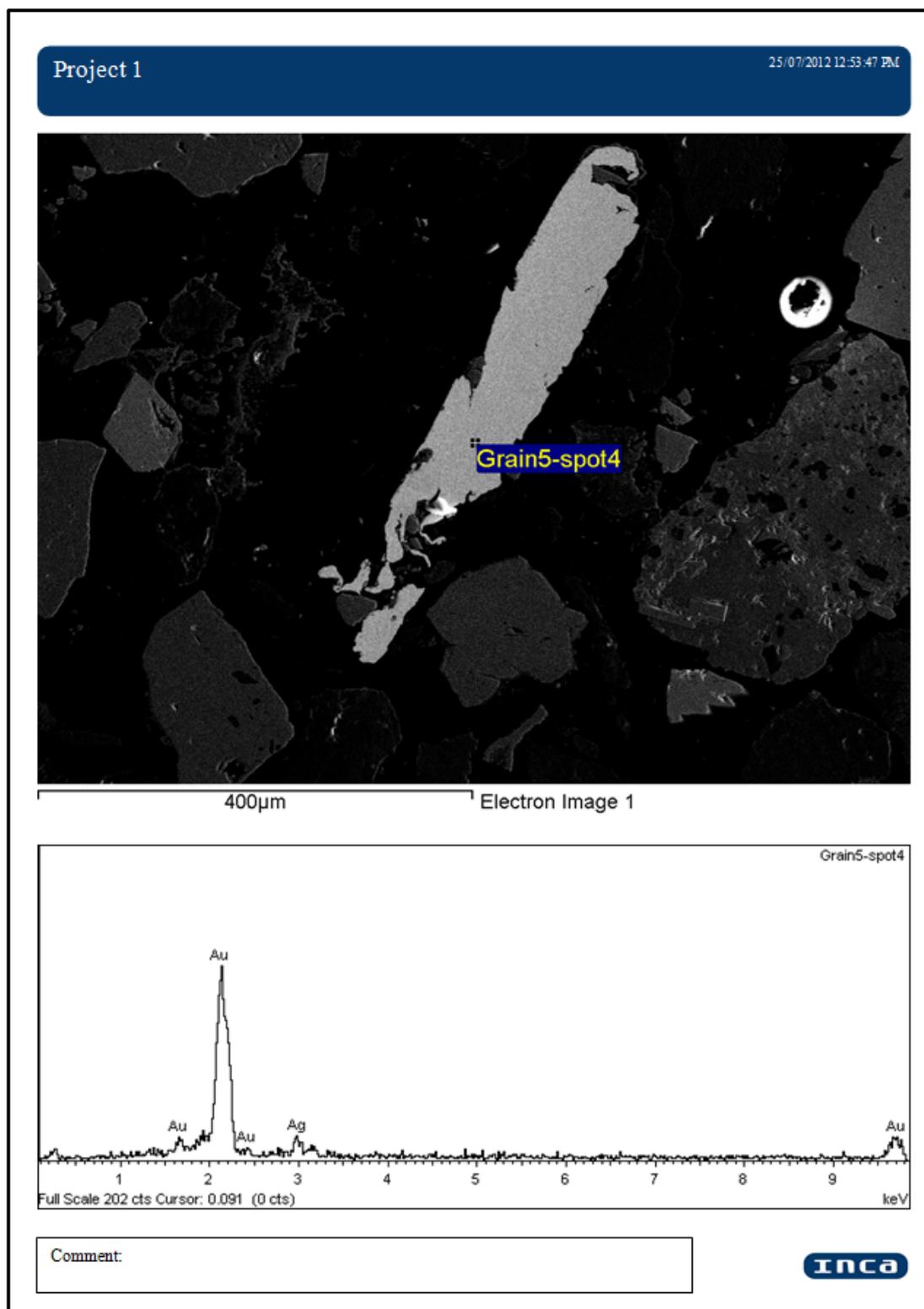


Figure 9-6. SEM-EDS image and spectra demonstrating elemental gold and silver occurrence at a particular spot of a particle of free gold from a BCC concentrate

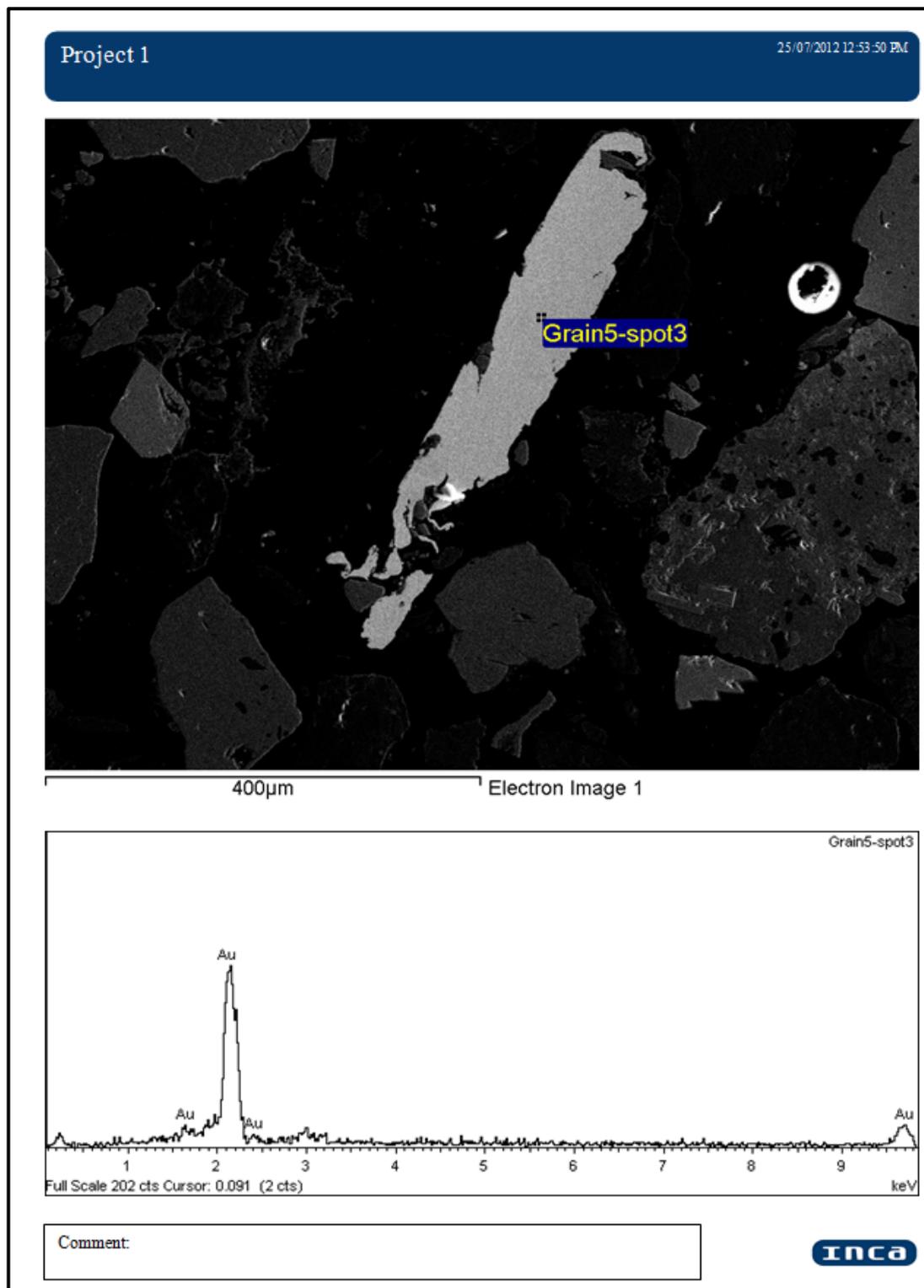


Figure 9-7. SEM-EDS image and spectra demonstrating elemental gold and silver occurrence at a particular spot of a particle of free gold from a BCC concentrate

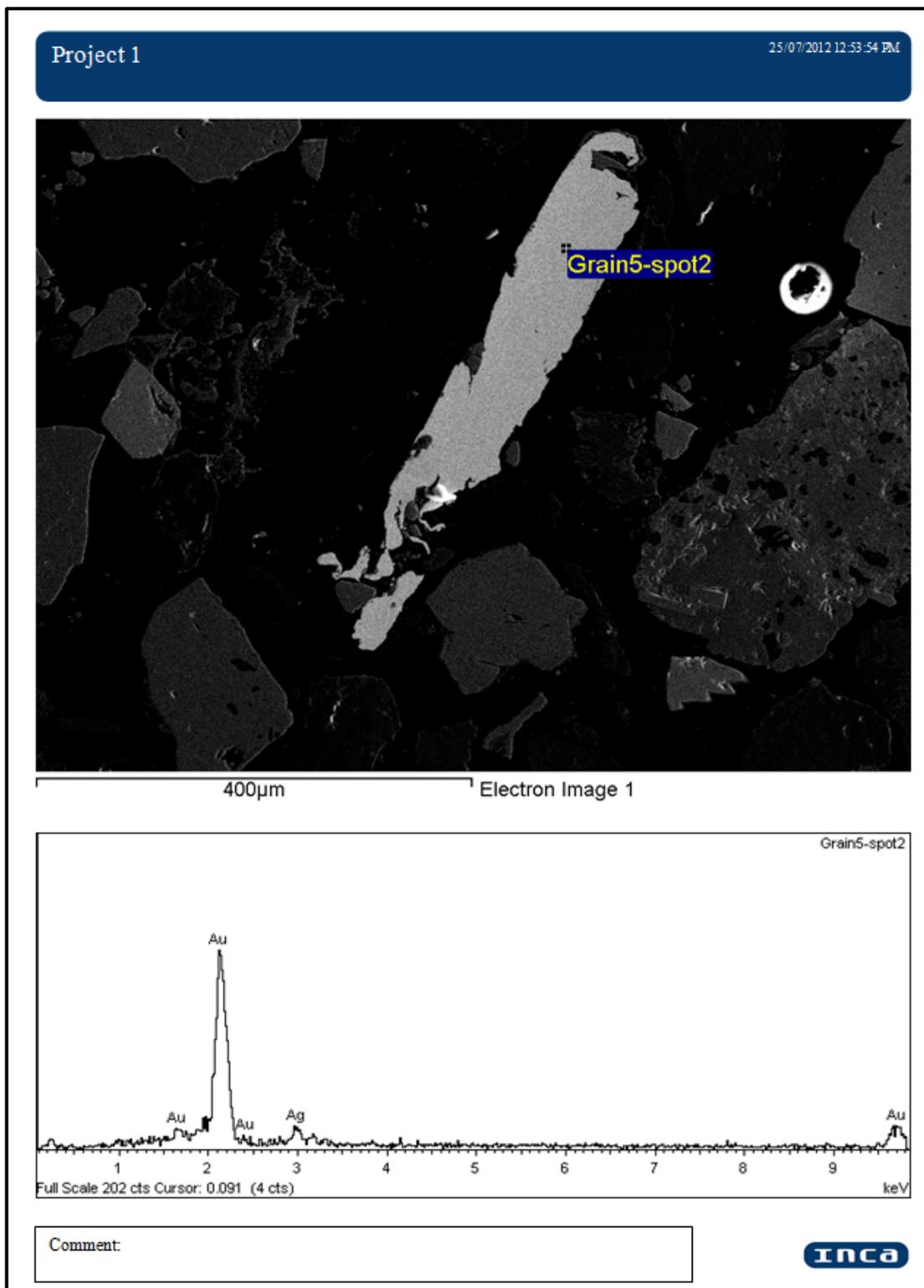


Figure 9-8. SEM-EDS image and spectra demonstrating elemental gold and silver occurrence at a particular spot of a particle of free gold from a BCC concentrate

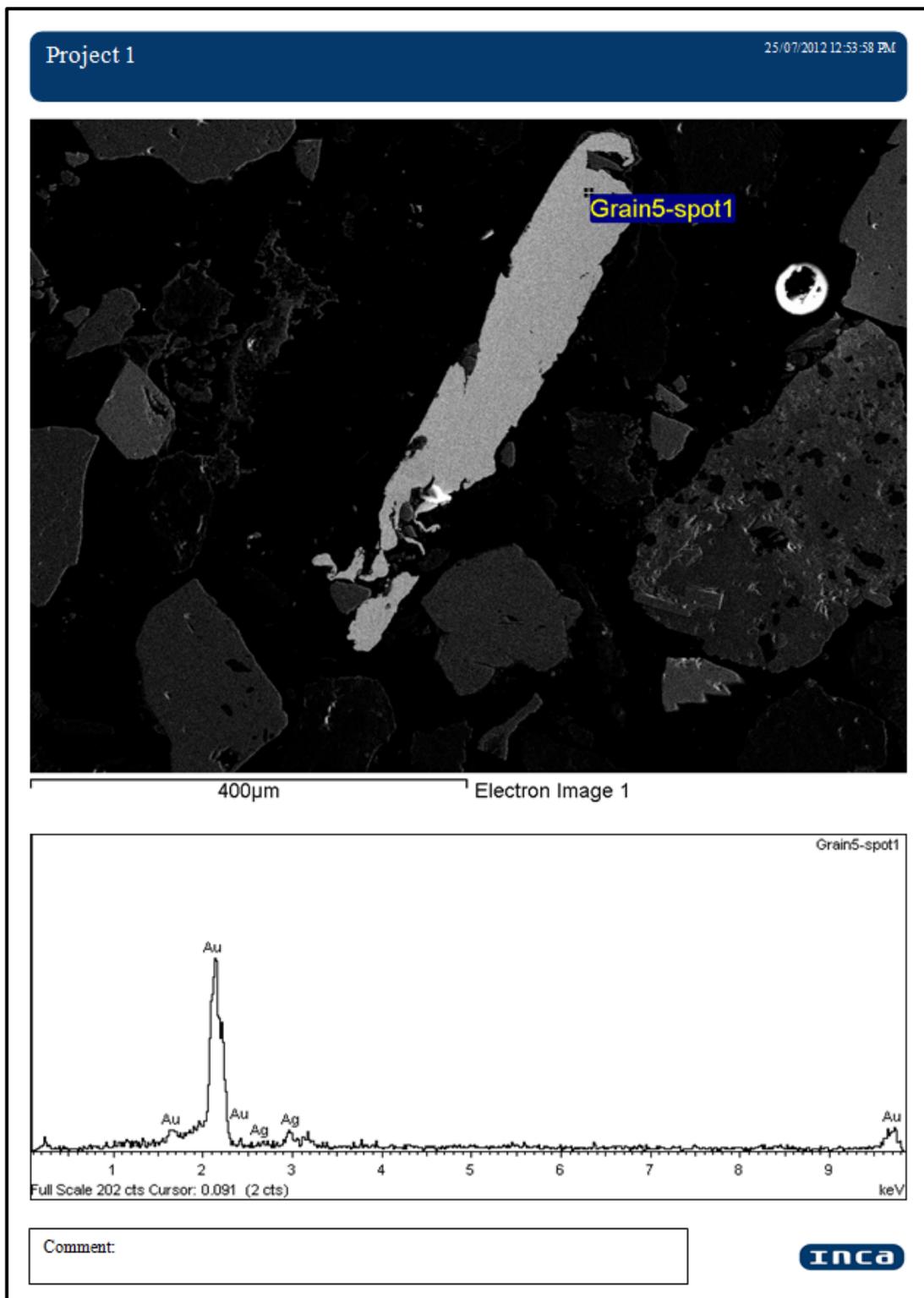


Figure 9-9. SEM-EDS image and spectra demonstrating elemental gold and silver occurrence at a particular spot of a particle of free gold from a BCC concentrate

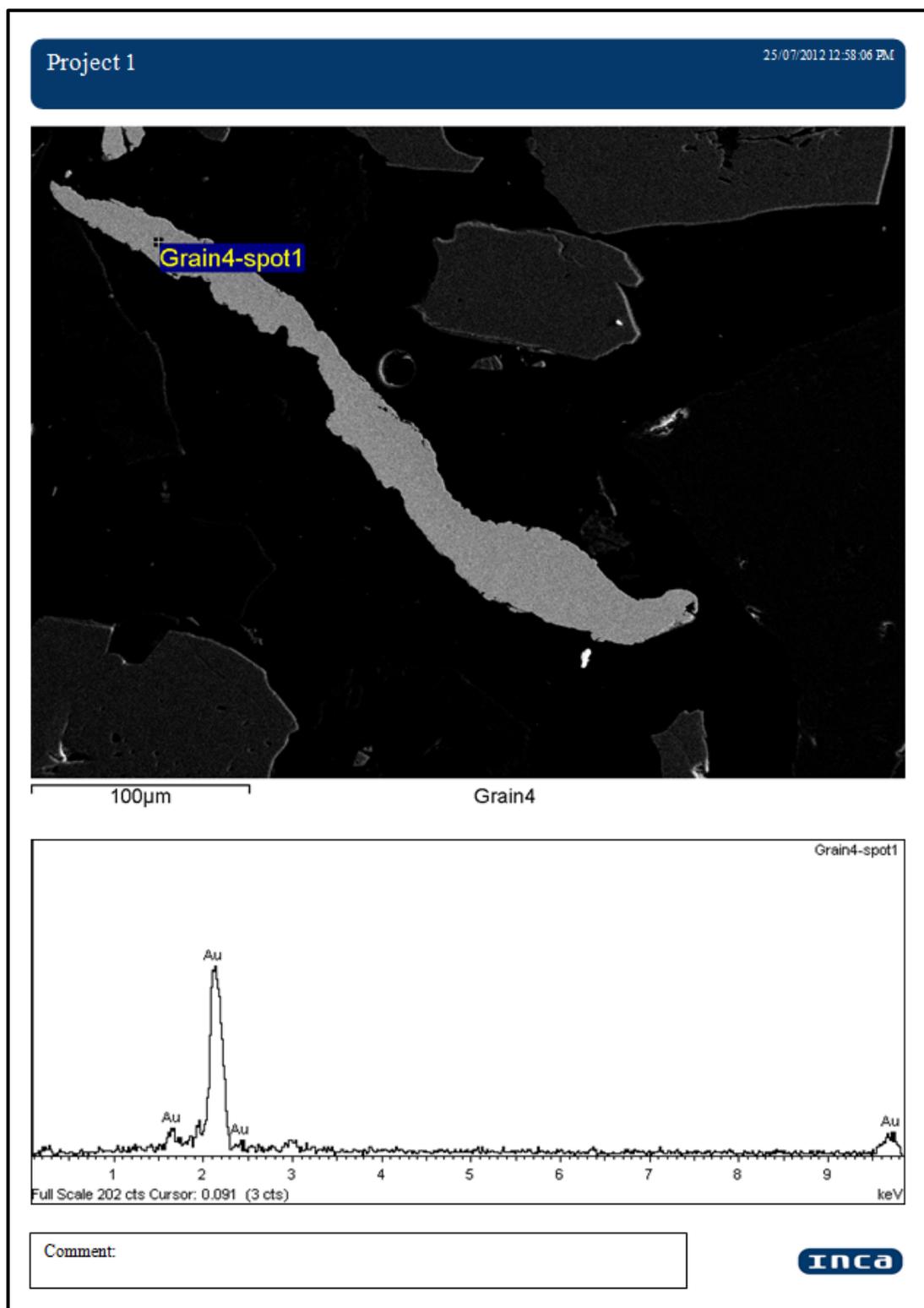


Figure 9-10. SEM-EDS image and spectra demonstrating elemental gold and silver occurrence at a particular spot of a particle of free gold from a BCC concentrate

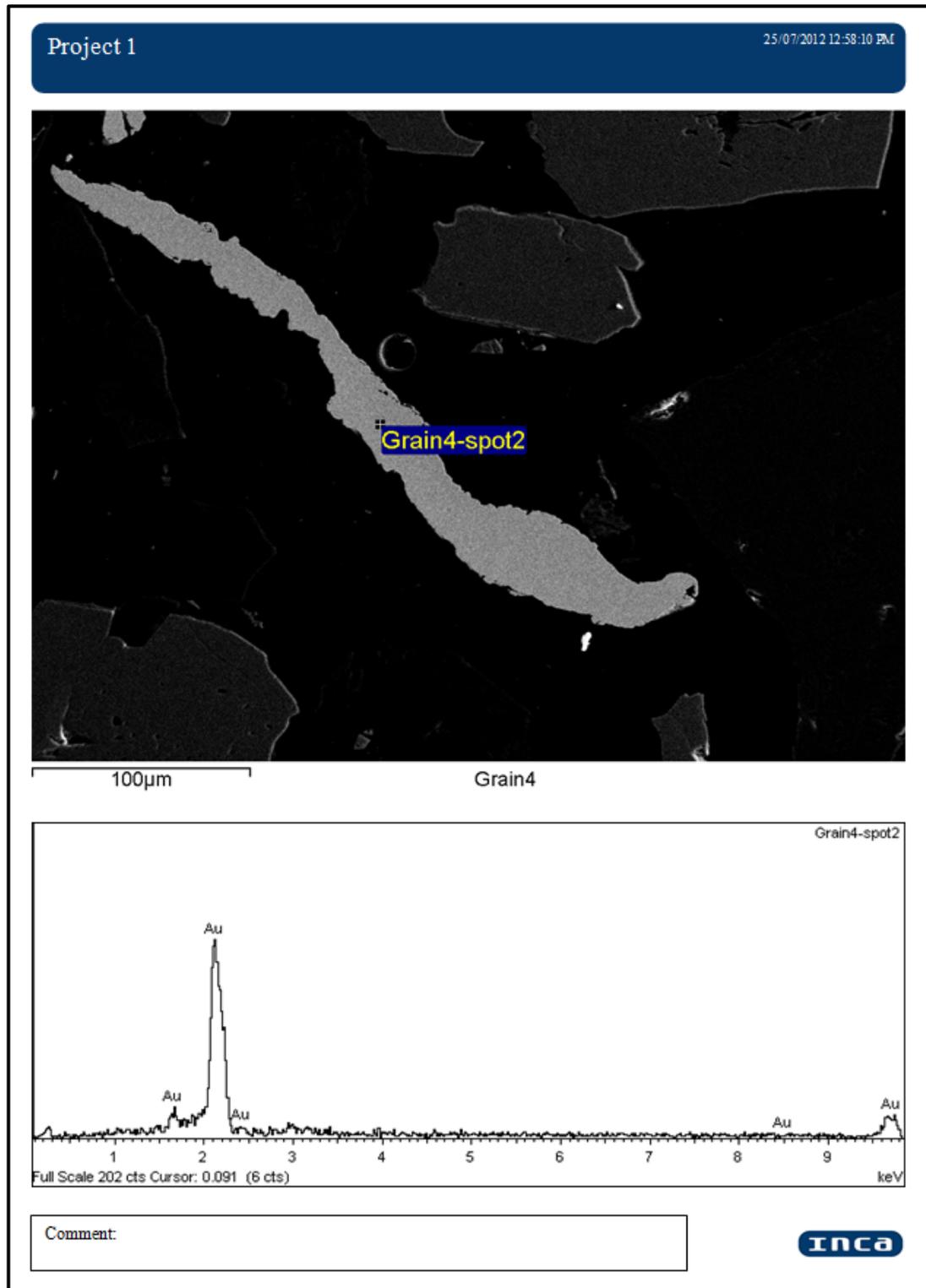


Figure 9-11. SEM-EDS image and spectra demonstrating elemental gold and silver occurrence at a particular spot of a particle of free gold from a BCC concentrate

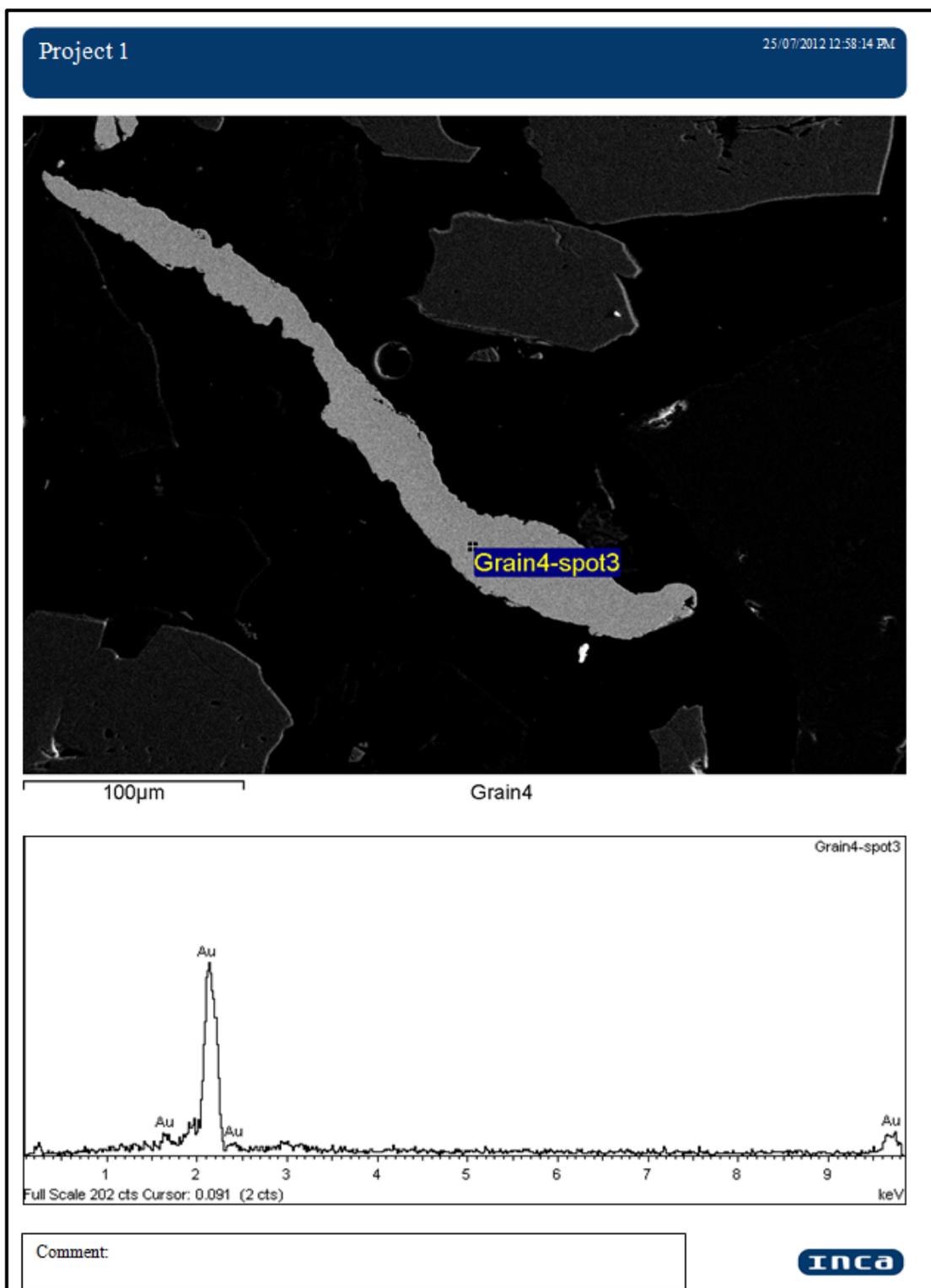


Figure 9-12. SEM-EDS image and spectra demonstrating elemental gold and silver occurrence at a particular spot of a particle of free gold from a BCC concentrate

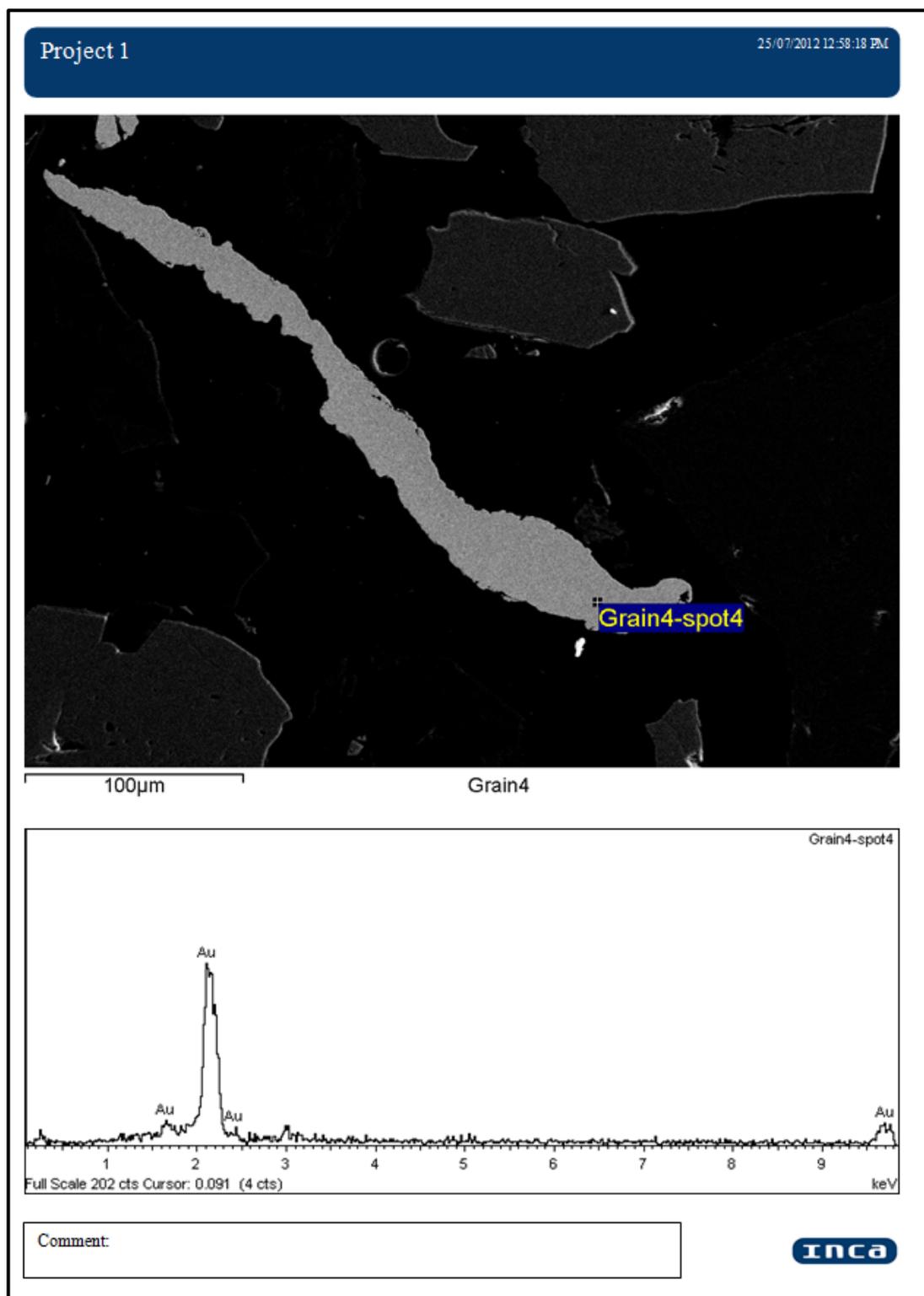


Figure 9-13. SEM-EDS image and spectra demonstrating elemental gold and silver occurrence at a particular spot of a particle of free gold from a BCC concentrate

9.4 Model Fitting Data

The following section includes data to the fit of expected concentration of gold in the flotation cell (C) to the concentration calculated by the three component system (C^*) for the experimental data in Chapter 5.

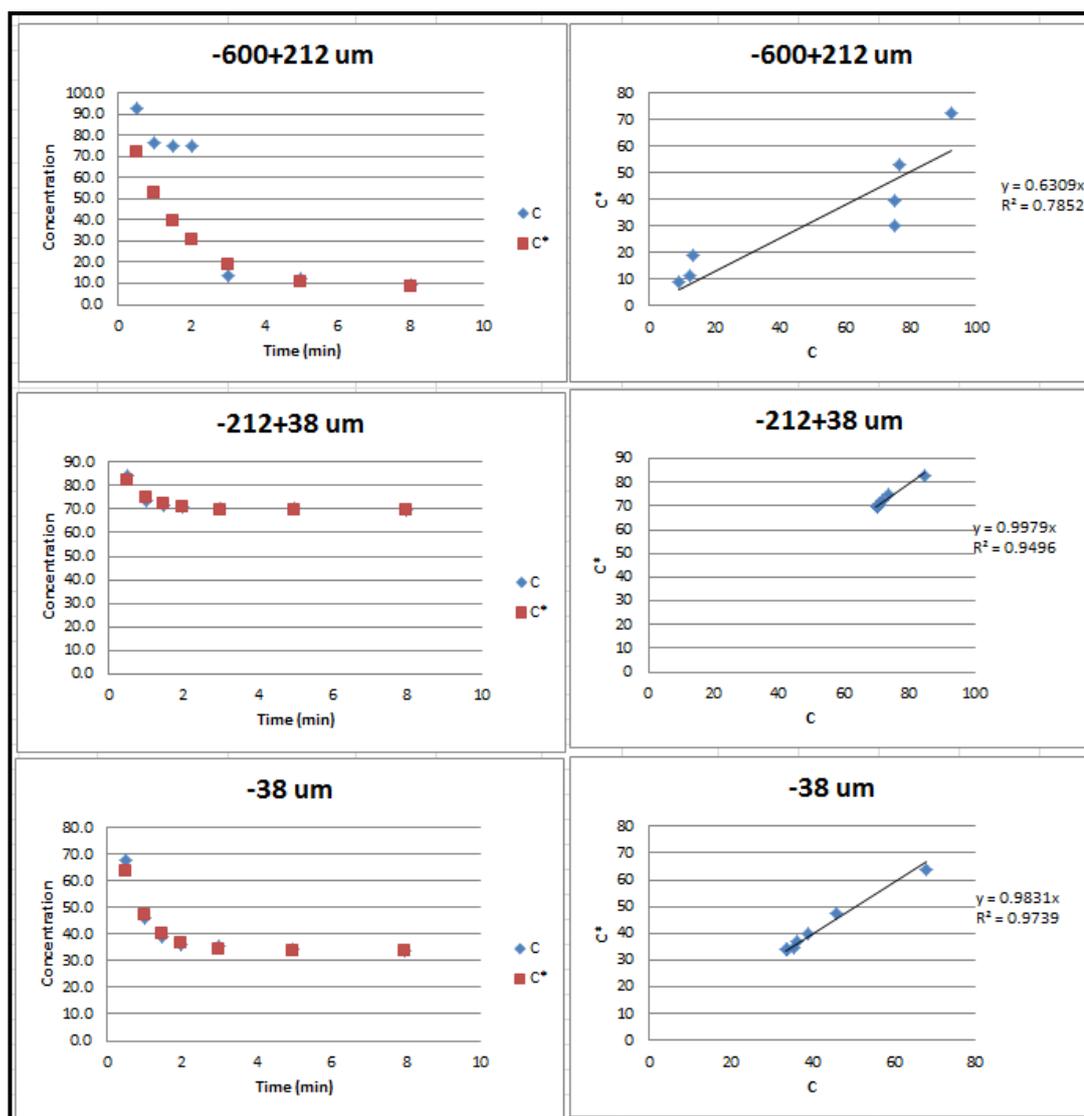


Figure 9-14. Comparison of fitted model (C^*) to actual recovery data (C) for Au powder at 50 g/t PAX

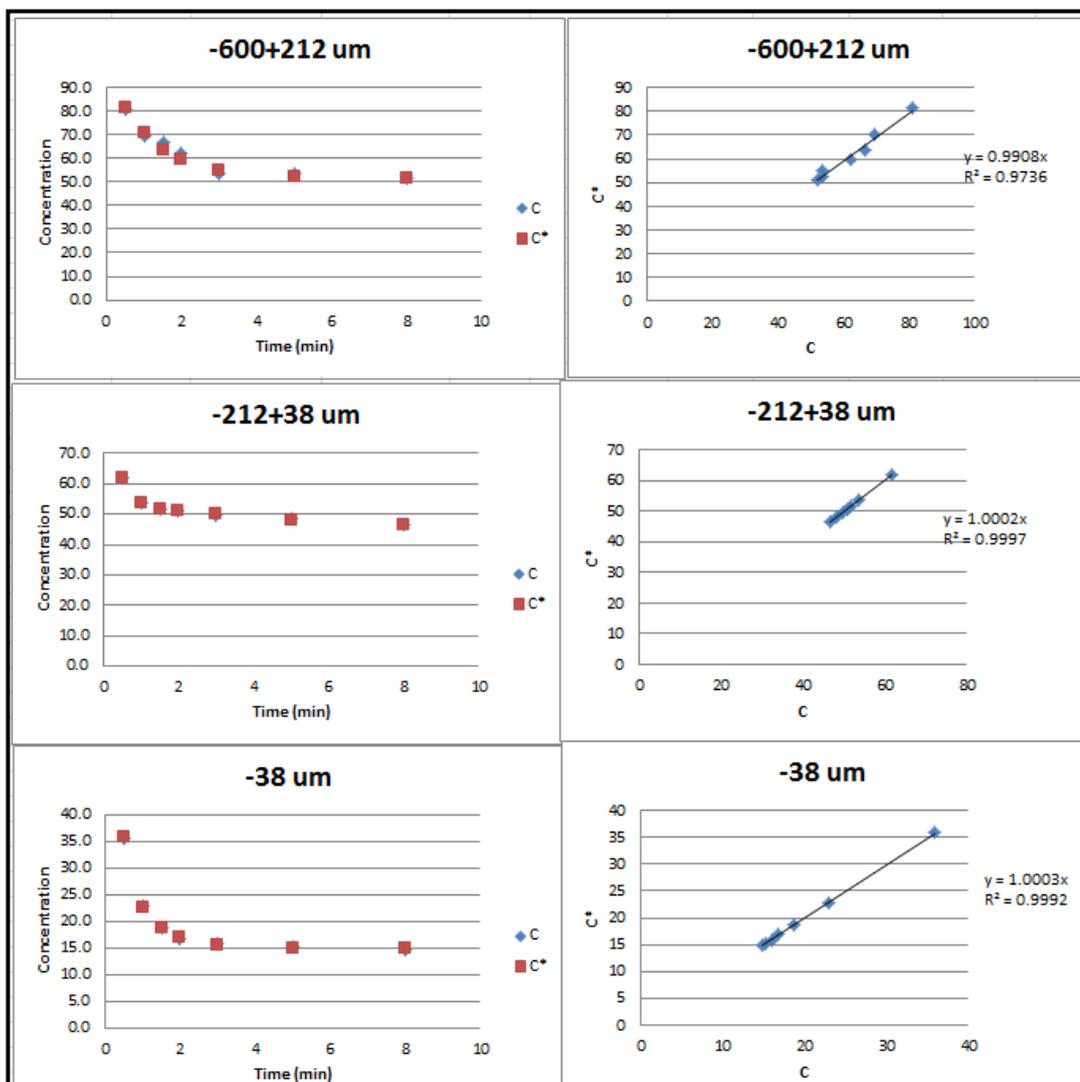


Figure 9-15. Comparison of fitted model (C*) to actual recovery data (C) for Au powder at 25 g/t PAX

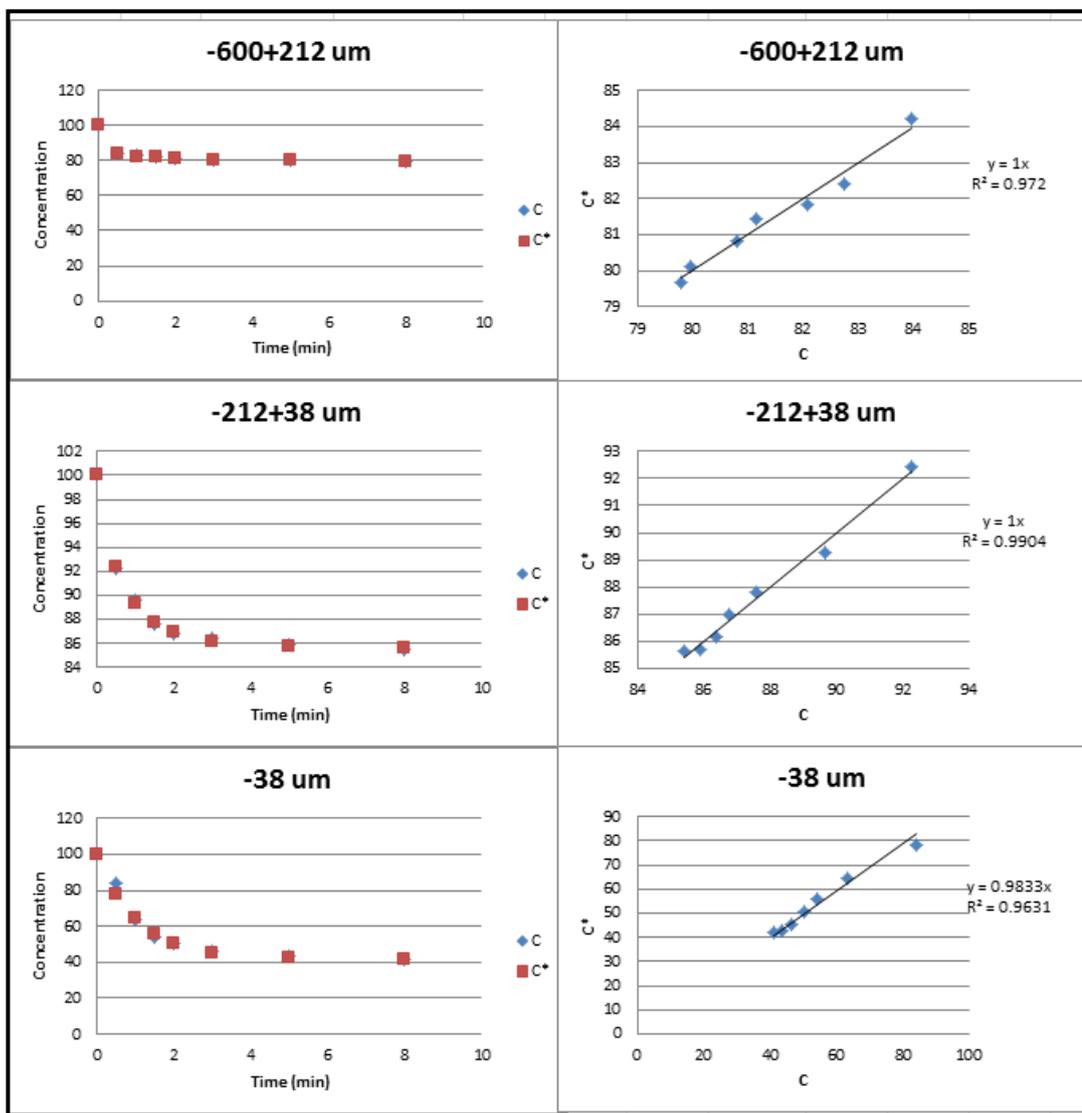


Figure 9-16. Comparison of fitted model (C^*) to actual recovery data (C) for Au powder at 0 g/t PAX.

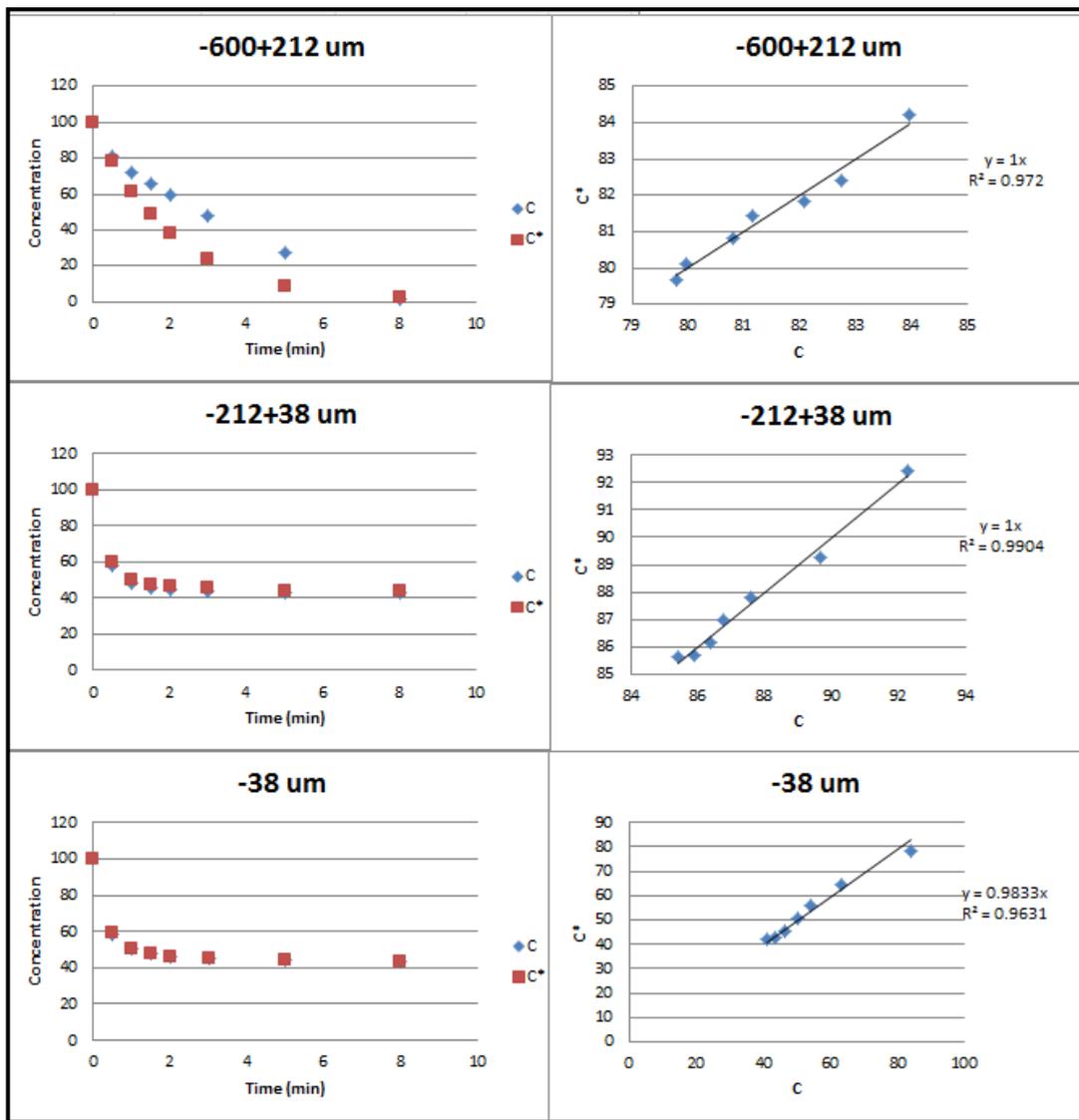


Figure 9-17. Comparison of fitted model (C*) to actual recovery data (C) for GRG concentrate at 50 g/t PAX.

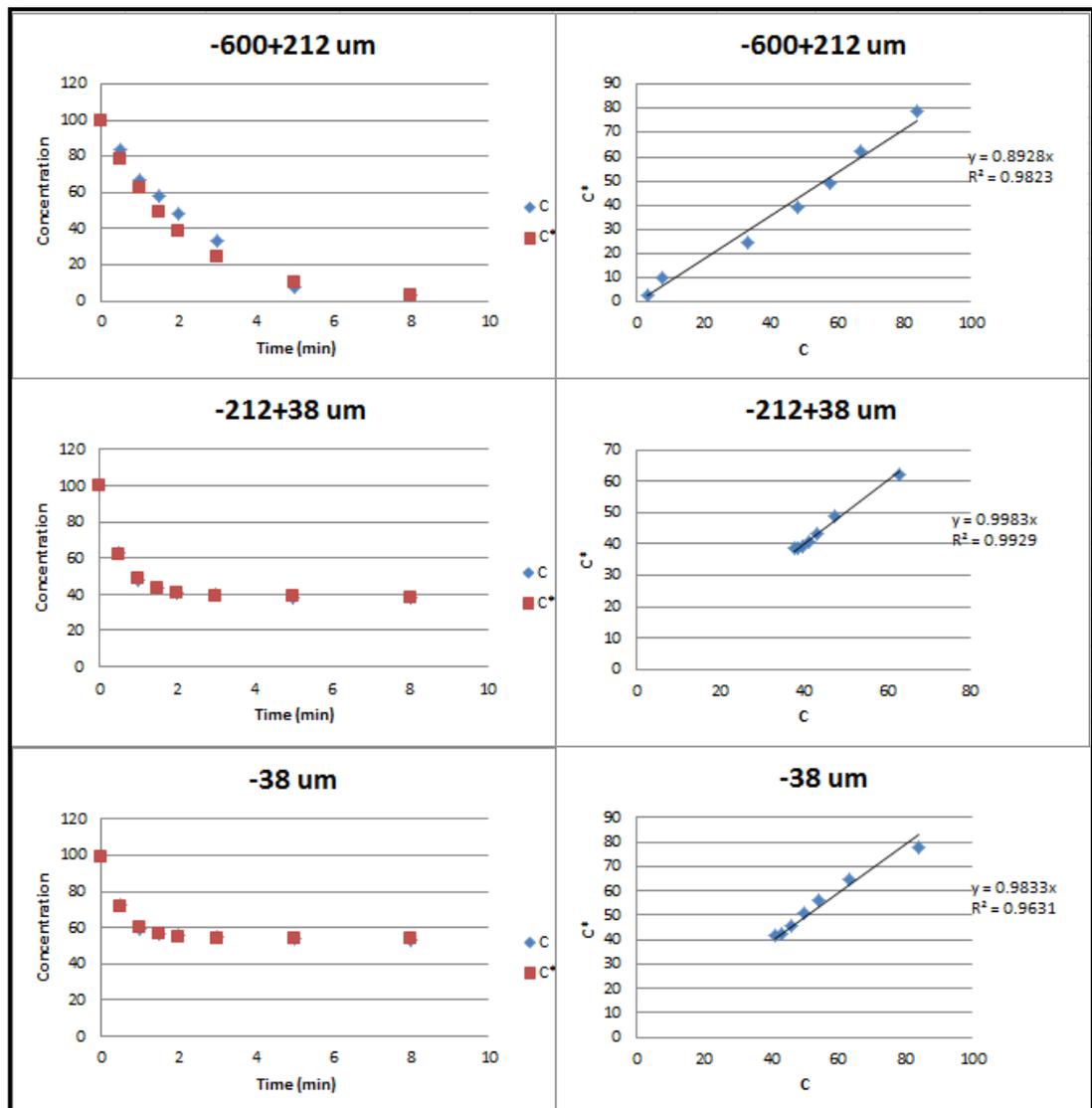


Figure 9-18. Comparison of fitted model (C*) to actual recovery data (C) for GRG concentrate at 25 g/t PAX.

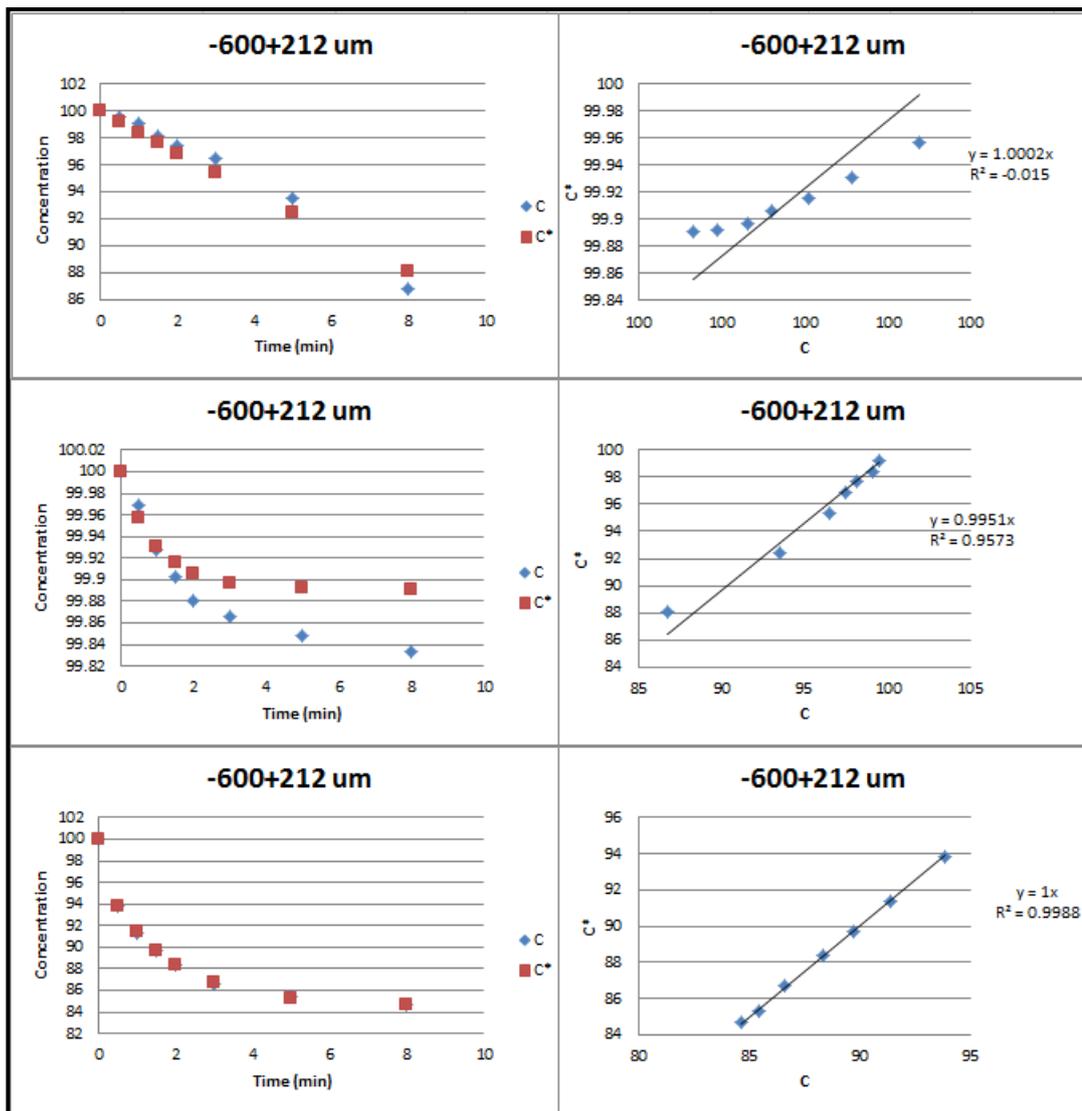


Figure 9-19. Comparison of fitted model (C*) to actual recovery data (C) for GRG concentrate at 0 g/t PAX.

9.5 Histograms for 2D Circularity Shape Determinations

The figures in this section demonstrate the frequency of particles in each circularity bin and estimated numbers of particles measured by QEMSCAN for each sample.

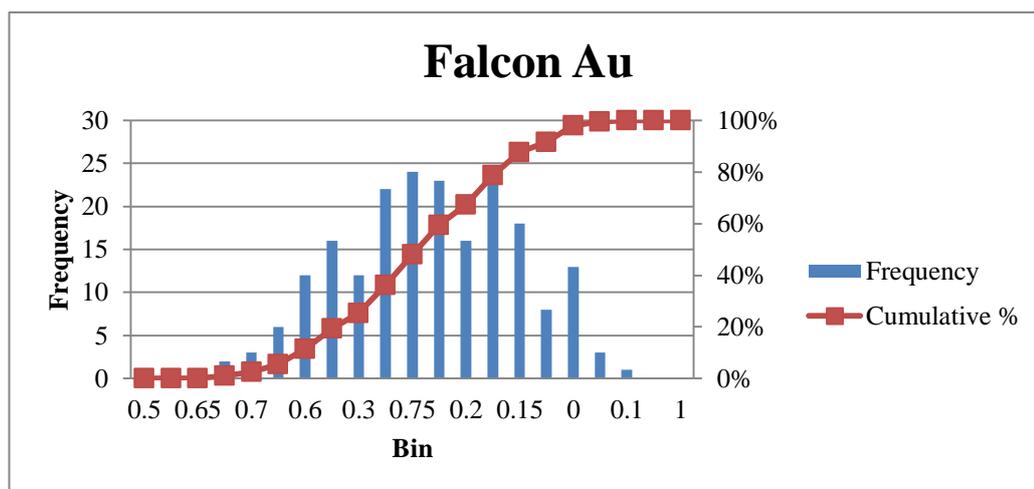


Figure 9-20. Histograms with gold particle counts for each bin identified for circularity determinations in the Telfer Falcon sample

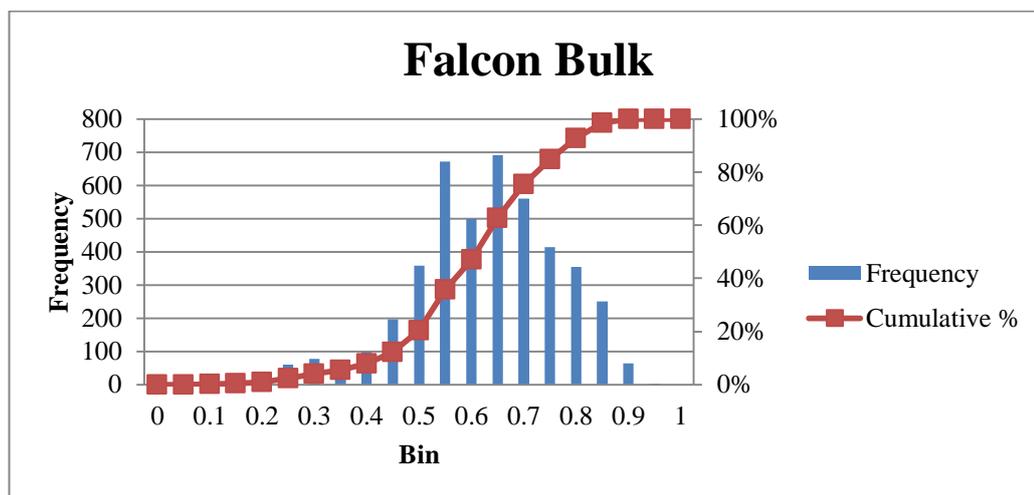


Figure 9-21. Histograms with bulk particle counts for each bin identified for circularity determinations in the Telfer Falcon sample

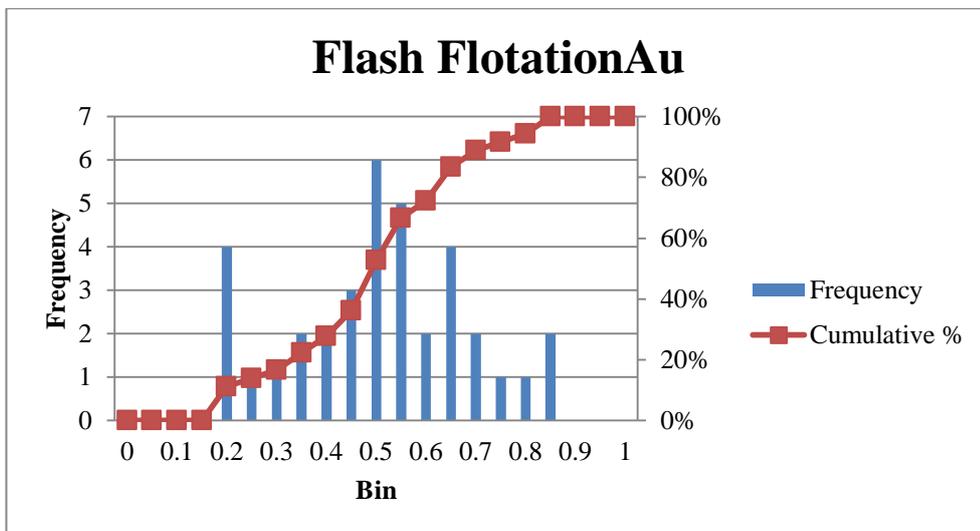


Figure 9-22. Histograms with gold particle counts for each bin identified for circularity determinations in the Telfer flash flotation sample

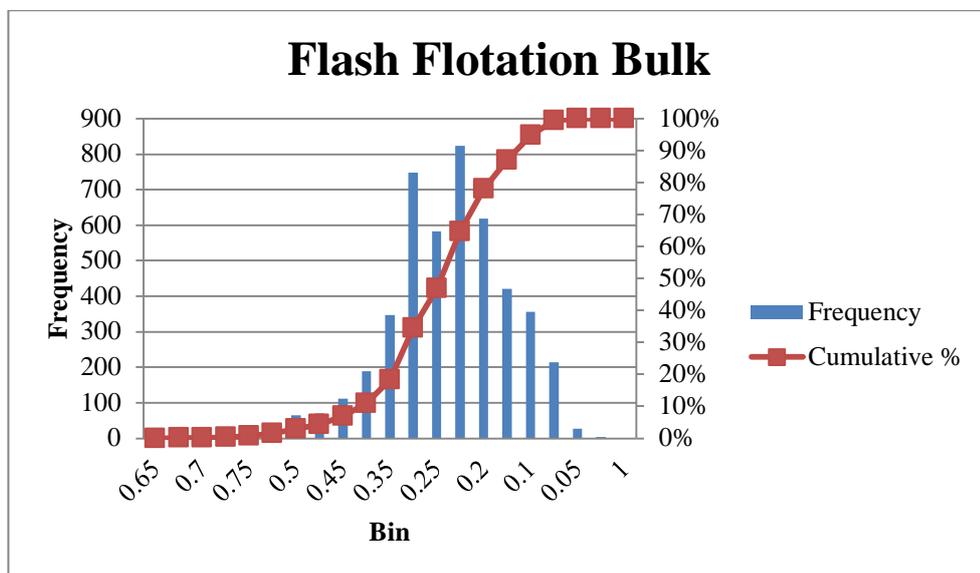


Figure 9-23. Histograms with bulk particle counts for each bin identified for circularity determinations in the Telfer flash flotation sample

9.6 Histograms for 3D sphericity and volumetric shape determinations

The figures in this section show the frequency of particles in each sphericity and volumetric shape bin as well as estimated numbers of particles measured by Micro CT for each sample.

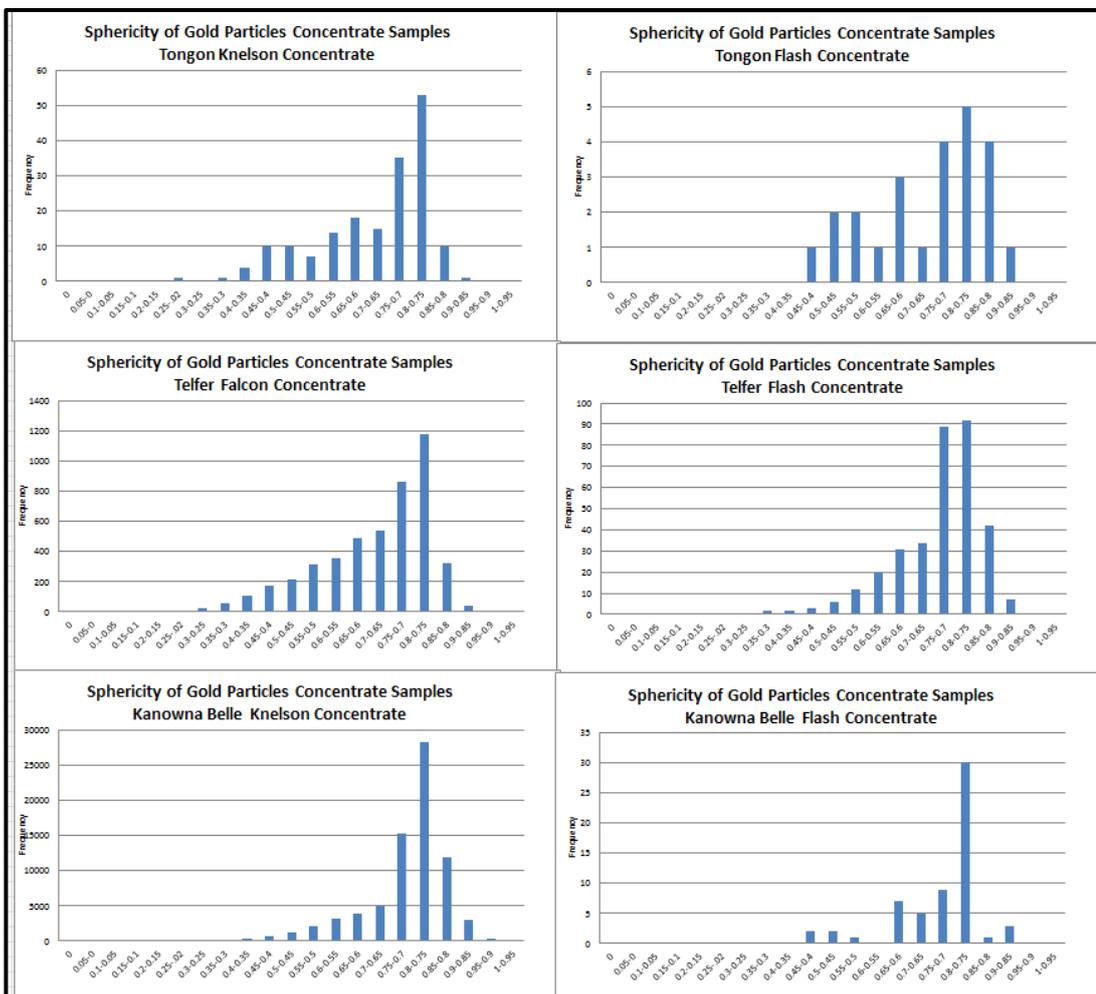


Figure 9-24. Histograms with particle counts for each bin identified for sphericity determinations

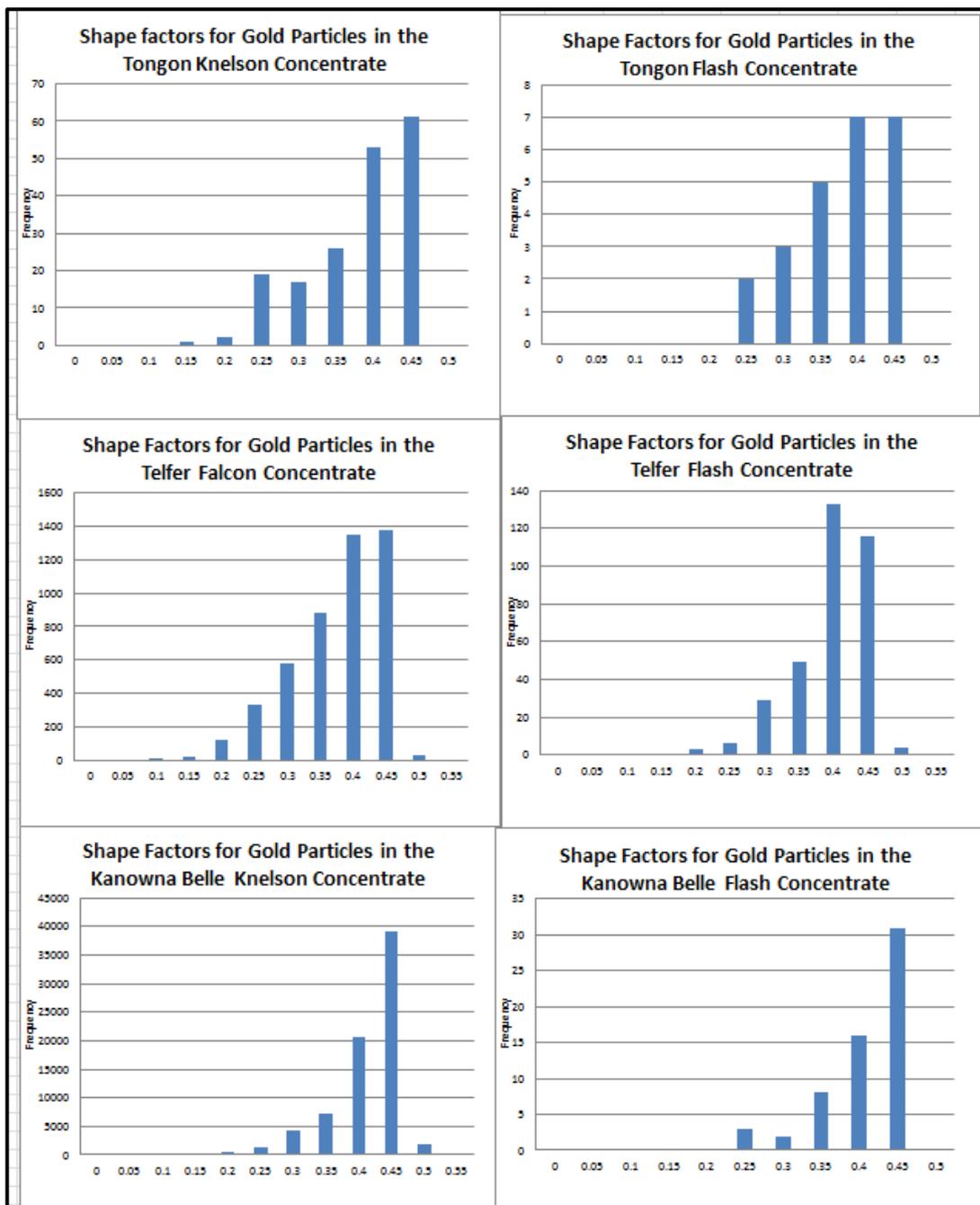


Figure 9-25. Histograms with particle counts for each bin identified volumetric shape determinations