SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

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PHYSICAL AND CHEMICAL CHARACTERIZATION OF MALAYSIAN SULPHIDE GOLD ORE FROM EAST PENINSULAR MALAYSIA

By

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DECLARATION

I hereby declared that I have conducted completed the research work and written dissertation entitled "Physical and Chemical Characterization of Malaysian Sulphide Gold ore from Eastern Peninsular Malaysia". I also declared that has not been previously submitted for the award of any degree or diploma or other similar of this for any other examining body of University.

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PENCIRIAN FIZIKAL DAN KIMIA TENTANG BIJIH EMAS SULFIDA MALAYSIA YANG BERASAL DARI SEMENANJUNG TIMUR MALAYSIA

ABSTRAK

Bijih emas sulfida diperolehi daripada Stok Simpanan Bijih Sulfida Gred Tinggi di Selinsing Gold Mine, Pahang. Kaedah yang digunakan di lapangan ialah pensampelan ambil dengan mengambil lebih kurang 25-30 tempat yang dipilih secara rawak, di bawah ½ daripada tinggi stok simpanan. Sampel dibahagikan kepada sampel pukal dan 5 pecahan saiz ayak: 90µm, 75µm, 50µm, 38µm and -38µm. Kedua-dua sampel pukal dan 5 pecahan saiz ayak dicirikan menggunakan X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD). Sampel bijih terutamanya terdiri daripada kuarza dan K-feldspar. Mineral sulfida utama adalah chalcopyrite, stibnite, pyrrhotite dan arsenopyrites. Sampel pukal digunakan dalam ujian fire assay, pelarutlesapan sianida secara terus dan kajian morfologi mengunakan mikroskop optik serta SEM/EDX daripada polish section. Emas didapati berkait dengan arsenopyrite, stibnite dan kuarza. Gred kepala didapati di dalam julat 0.954 g/T berdasarkan keputusan fire assay manakala pelarutlesapan sianida secara terus memberikan pulangan 83% menunjukan bijih emas sulfida ini boleh diklasifikasikan sebagai separa refraktori.

PHYSICAL AND CHEMICAL CHARACTERIZATION OF MALAYSIAN SULPHIDE GOLD ORE FROM EAST PENINSULAR MALAYSIA

ABSTRACT

The sulphide ore samples are obtained from the High Grade Sulphide Ore stockpile at Selinsing Gold Mine, Pahang. The method used on the site is grab sampling by taking about 25-30 randomly chosen spots, below ½ of the stockpile height. The samples are divided into bulk sample and 5 sieve size fractions: 90µm, 75µm, 50µm, 38µm and -38µm. Both bulk sample and the 5 size fractions were characterized using X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD). The ore samples primarily compose of quartz and K-feldspar (microcline). The main sulphide minerals are chalcopyrite, stibnite, pyrrhotite and arsenopyrites. Bulk sample are subjected to fire assay analysis, direct cyanide leaching and morphological study using optical microscope and SEM/EDX of polish section. The gold was found associated with arsenopyrite, stibnite and quartz. The head grade was found to be in the range of 0.954 g/T based on fire assay result while direct cyanide leaching gives 83% recovery indicates that the sulphide ore sample can be classified as partly refractory.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Mining of gold in Malaysia is believed had begun two thousand years ago. Indian travellers called the Malaysia Peninsula, 'Suvarna Bumi' or 'The Golden Land', while Ptolemy, a second century Alexandrian geographer used the phrase, 'Golden Chersonese' or 'Golden Peninsula'. Malaysia has a long history of widespread small-scale gold mining throughout the country, especially in the Central Belt of Peninsular Malaysia and highly potential region for the gold mining industry. The Central 'Gold Belt' is a 20km wide, a major N-S trend of gold mining districts that shows the important role of hydrothermal fluids in the development of gold in Peninsular Malaysia, especially in the North Pahang and Kelantan area (Khamar Shah, 2012). The production of gold during the early years of mining was around 3000 kilograms of raw gold, which has increased to an estimated 4625 kilograms of raw gold production in 2012. This throws a clear indication as to where this industry is leading in the future. The Selinsing gold deposit is located in northwest Pahang, approximately 50km north of Raub Town in central Malaysia. The Selinsing deposit and other major gold deposit in the region such as Ulu Sokor, Pulai, Buffalo Reef, Penjom and Raub deposits are located to the east of the Bentong-Raub Suture Zone. Ore minerals at the Selinsing gold deposit include pyrite, arsenopyrite, galena, sphalerite, chalcopyrite, pyrrhotite and gold. Gangue minerals include ankerite, rutile, sericite, hematite, calcite, illite and chlorite. (Makoundi *et al.*, 2014). Gold is present in refractory sulfide gold ores are mainly in arsenian pyrite and arsenopyrite, where it occurs in both the chemically bonded state and as nano-size grains of metallic gold (Chen, Cabri and Dutrizac, 2002). The sulfide gold ore is a complex ore which required a specific observation and study to extract the gold from its ore due to its high economic value.

1.2 Significant of Research Project

Conventional method of extracting gold from gold ores is by using cyanide leaching circuits. Gold ores that do not yield high recoveries using this method even after finely ground is considered as refractory ores. In order to extract the gold, these type of ores required more reagents and more pre-treatment processes. Hence, making the processing route more complex. The mineral assemblage inside the ores will greatly determine the outcome of the extraction process. Therefore, it is crucial to understand the mineralogy of the ores to be processed. There have been great deal of work been done to characterize gold ores especially refractory ores. Gold price had been increasing steadily during this past few years. However, the free-milling gold ores deposits had become scarce, hard to find and the current deposits which are being mine are depleting. On the other hand, more refractory ores like sulphide gold ores are being discovered and processed during those years. This shows how important gold characterization to the industry as it helps to solve various problems faced during the processing of complex gold ores. Understanding of the mineralogy of the ores also helps in reducing the overall processing cost, making it more profitable by avoiding unnecessary process and enable the optimization of the amount of reagents used during the process. As a result, proper processing flowchart which are able to obtain good gold recoveries can be designed based on the result of the characterization of the specific complex gold ores.

1.3 Problem Statement

The mineral formation of gold varied with the location of deposit. In this research, the sulfide gold ore is obtained from the Selingsing Mine, located in East Peninsular Malaysia. Different type of ore will have different mineral composition. Sulphide gold ore is considered as refractory gold ore where those gold ores do not yield high recoveries in conventional cyanide leaching circuits. When gold is associated with sulfides, it can be either fully encapsulated by the sulfide particle or partially liberated, i.e. exposed on the edge of the sulfide mineral.(Chen, Cabri and Dutrizac, 2002) The purpose of subjecting refractory sulfide gold ores to mineralogical examination is to identify the mineral composition of sulfide gold ore from East Peninsular Malaysia and to determine the associated mineral of the sulfide gold ore. When properly characterized, sulfide complex gold ores can be efficiently processed and increase the gold recovery.

1.4 Objectives

The objectives of this research are as below :

- To determine mineral composition of sulfide gold ore from East Peninsular Malaysia
- To identify associated mineral of the sulfide gold ore
- To determine the gold content from the bulk ore samples using Fire Assay Technique and the free mill gold content via direct cyanidation.

1.5 Scope of Study

In this study, the samples are raw sample which are directly collected from the High Grade Sulphide Ore stockpile at Selinsing Gold Mine, Pahang. The samples comprises of bulk rocks and soils. The method used on the site is grab sampling by taking about 25-30 randomly chosen spots, below ½ of the stockpile height. Total weight of the sample taken is about 68.6 kg which then undergoes crushing using jaw and cone crusher to reduce the size. To obtain the representative samples, the sample were split using cone and quartering method and John's Riffle Splitter which reduce the sample down to 1.73 kg. Ring mill is used to grind the samples before it becomes suitable for characterization process.

The samples are divided into bulk sample and 5 sieve size fractions: 90µm, 75µm, 50µm, 38µm and -38µm. Both bulk sample and the 5 size fractions are subjected to characterization analysis using elemental composition analysis (XRF) and phase identification (XRD). This enables to determine if the gold preferentially concentrated in a particular size fraction and its mineral composition.

Bulk sample are subjected to fire assay analysis, bottle roll cyanidation leach test and morphological study using optical microscope and SEM/EDX of polish section. Fire assay analysis is carried out to determine the amount of bulk gold content inside the sulphide ore samples. The cyanidation leach test is used to quantify the gold that can be extracted via direct cyanidation i.e liberated gold, free and exposed after milling process.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Current gold production shows a positive development. In 2005, world gold production amounted to 2,470 metric tons. From that point forward, world gold production expanded consistently up to an estimated 3.15 thousand metric tons in 2017 (*World Gold Production*, 2017). China was the largest gold producer in the world in 2016, accounting for around 14% of total annual production, but no one region dominates. Asia as a whole produces 23% of all newly-mined gold. Central and South America produce around 17% of the total, with North America supplying around 16%. Around 19% of production comes from Africa and 14% from the CIS region. (*Mine Production*, 2016). This throws a clear indication as to where this industry is leading in the future.

World demand for gold keeps growing over the years which stimulates the needs for research work to be done regarding this subject. This paper intend to describe the physical and chemical characterization done on the sulphide gold ore collected from Selinsing Gold Mine stockpile. In this chapter, everything which is related to the study of gold is reviewed back based on the available literatures including all the fundamental definition, gold mineralogy, geological, site background and anything which is considered relevant about the subject.

2.1.1 Mineral

Mineral can be defined as naturally occurring inorganic substance with definite ordered atoms arrangement and chemical composition (Wills and Napier-munn, 2006). Naturally occurring inorganic means the formation of the mineral occur naturally and does not involve living organisms. Definite ordered atoms arrangement means that the atoms within the mineral are arranged systematically with a specific pattern. Definite chemical composition means each type of mineral is made of specific chemical composition (M.King, 2005). Whereas rock can be define as aggregates of different minerals. Minerals are categorized by various physical and chemical properties, which are related to their chemical structure and composition. Common characteristics of the mineral which differentiate one mineral from another include crystal structure and habit, hardness, lustre, diaphaneity, colour, streak, tenacity, cleavage, fracture, parting, specific gravity, magnetism, taste or smell, radioactivity, and reaction to acid. It can be classified into several mineral groups which is sulphides, oxides, halides, carbonates, phosphates, silicates and native element

2.1.2 Ore minerals

Ore minerals are the rock or sediment that have sufficient valuable mineral within it which make it economically viable to be extracted through mining. Ore minerals comes together with gangue minerals which is the unwanted or waste mineral. This minerals are separated during mineral processing using either or combination of both physical and chemical method. Ore mineral also classified into two groups which are metallic and non-metallic minerals. The processing circuit are designed based on the physical and chemical properties of the wanted valuable mineral itself.

2.1.3 Gold application and uses

Gold has been highly valued by men since the early of time. Its rarity is one of the major which makes gold very valuable. Gold mineral occur as one of the native elements. Native element are those element that exist naturally in uncombined form with distinct mineral structure. It usually associates with quartz and pyrite. It is the most useful metal mined from the earth. Its usefulness derived from a diversity of special properties. The melting and boiling point for pure gold is 1377.33 K and 3243 K respectively. Gold is a good electric conductor, does not tarnish, can be hammered into thin sheets, have attractive color and a brilliant lustre. Since it is malleable and ductile, artists and craftsmen can shape it into something even more beautiful. (Brian Belval, 2007). Primarily, gold is used as jewelry and coinage but it also can be used in electronics, medicine, optic and even in aerospace technology. Its rarity, usefulness, and desirability make it command a high price.

2.1.4 Geological of gold

Gold is formed through complex geological process, it occurs in many different kinds of rocks and in many different geological environments. Generally, there are two types of gold deposit: lode (primary) deposits and placer (secondary) deposits.

Lode deposit is when the gold become deposited at the site of the mineralizing solution. There are various hypothesis proposed by the geologist to explain about the source of the solution. The most accepted hypothesis proposes that many gold deposits, especially those found in volcanic and sedimentary rocks, formed from circulating ground waters driven by heat from bodies of magma (molten rock) intruded into the Earth's crust within about 2 to 5 miles of the surface. Most of the water in geothermal systems originates from rainfall, which moves downward through fractures and permeable beds in cooler parts of the crust and is drawn laterally into areas heated by magma, where it is driven upward through fractures. As the water is heated, it dissolves metals from the surrounding rocks. When the heated waters reach cooler rocks at shallower depths, metallic minerals precipitate to form veins or blanket-like ore bodies.

Placer deposits represent concentrations of gold derived from lode deposits through weathering process. This involves erosion, disintegration or decomposition of the parent rock (gold bearing rock), transportation and subsequent concentration by gravity. Gold is both highly resistant to weathering and has high density. Hence, when freed from the parent rocks, they are carried downstream as metallic particles consisting of "dust," flakes, grains, or nuggets. This gold particles are carried downstream, concentrated and redeposited at the trap site. Trap site is where the water velocity remains below that required to transport them further. Typical locations for alluvial gold placer deposit are on the inside bends of rivers and creeks (Harold Kirkemo, William L. Newman, 1997)

2.1.5 Sulphide gold ore

Sulphide gold ore means that the gold ore contain sulfides. Sulphide gold ore is considered as refractory gold ore where those gold ores do not yield high recoveries in conventional cyanide leaching circuits. When gold is associated with sulfides, it can be either fully encapsulated by the sulfide particle or partially liberated, i.e. exposed on the edge of the sulfide mineral.(Chen, Cabri and Dutrizac, 2002) Gold is present in refractory sulfide gold ores are mainly in arsenian pyrite and arsenopyrite, where it occurs in both the chemically bonded state and as nano-size grains of metallic gold.(Chen, Cabri and Dutrizac, 2002)

2.2 Site Background

2.2.1 Selinsing Goldfield

It is located in NW Pahang, Peninsular Malaysia, approximately 50 km north of Raub Town in central Malaysia. The Selinsing deposit and other major gold deposits in the region such as the Ulu Sokor, Pulai, Buffalo Reef, Penjom, and Raub deposits are located to the east of the Bentong-Raub Suture Zone. The Selinsing deposit has a long mining history tracing back prior to the late 19th Century. Currently, the Selinsing Gold Mine Project contains an indicated mineral resource of 4.82 million tons at 1.49 g/t Au, using a cut-off grade of 0.59 g/t Au for contained gold of 231,000 oz, and an inferred mineral resource of 10.32 million tons at a grade of 1.17 g/t Au for contained ounces of 388,000 at a similar cut-off grade. In 1933, the Geological Survey of Malaysia undertook geological mapping and reported that the Selinsing gold deposit is located within Permo-Triassic sediments in close proximity to Post-Triassic granites and the Pahang volcanic series composed chiefly of Carboniferous to Triassic tuffaceous rocks (Makoundi *et al.*, 2014). The area consists of low-grade metamorphosed sedimentary and volcanic rocks of Gua Musang Formation of Late Permo-Triasic age. Based on the wall rock alteration in Selinsing Gold mine, it shows a direct relation with hydrothermal solution, structures, formation of quartz veins and gold mineralization (Khamar Shah, 2012). The Selinsing deposit take place along the north striking Raub Bentong Suture. Series of auriferous quartz veins and stockworks of quartz veinlets in a package of sheared calcareous epiclastic sediments present in the deposit. The gold mineralisation occurs in quartz veins that cut the host rocks and wall rocks with intensive alteration that are associated to the N-S and NE-SW lateral faults and shear zones (Basori, Abdullah and Hassan, 2009). Gold mineralization at Selinsing is associated with high grade quartz veining and accompanied by strong sericitization and silicification within a major shear zone. Formations of quartz veins are mainly related to the right lateral faults. Minerals regularly associated with gold mineralization are pyrite, arsenopyrite, chalcopyrite, tetrahedrite and sphalerite (Hassan, Basori and Abdullah, 2008).

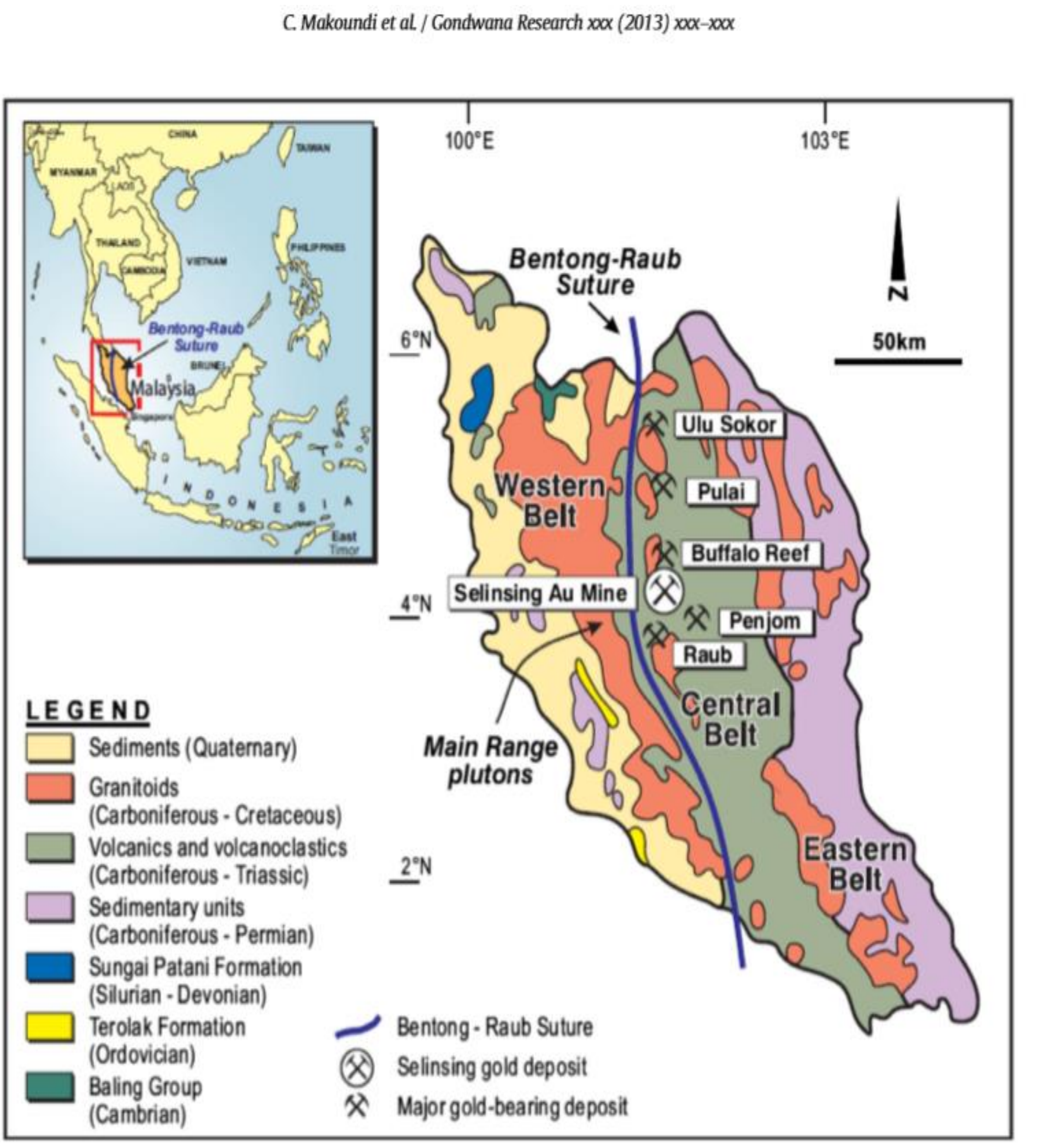

Figure 2.1: Map showing the location of the Selinsing and other gold deposits, Bentong-Raub Suture Zone, the Western, Central, and Eastern Belts in Peninsular Malaysia. Modified from Makoundi (2012,p.19).

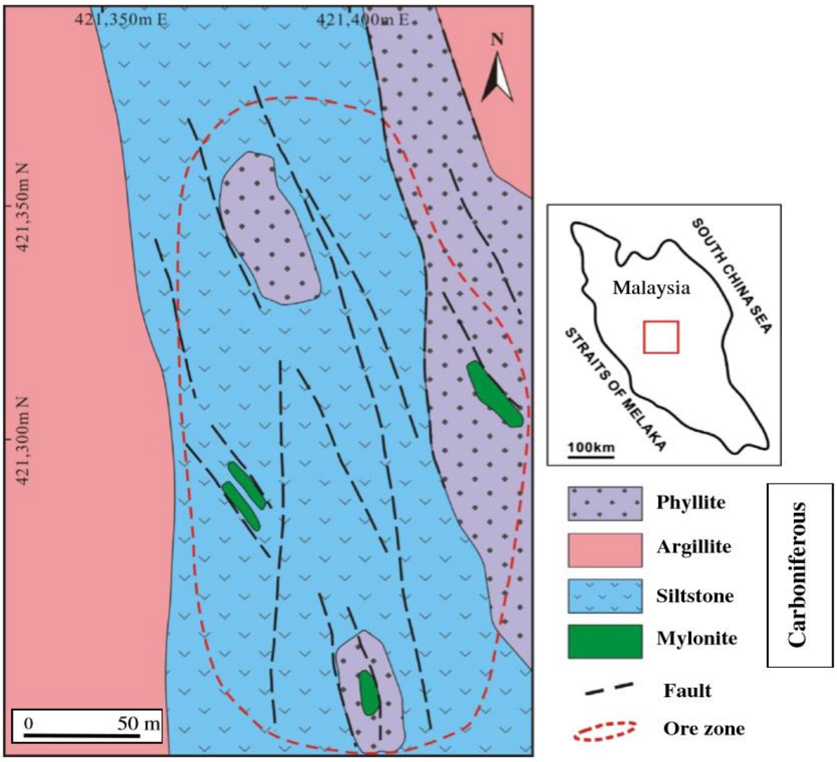

Figure 2.2: District-scale geological map of the Selinsing gold deposit, Central Malaysia

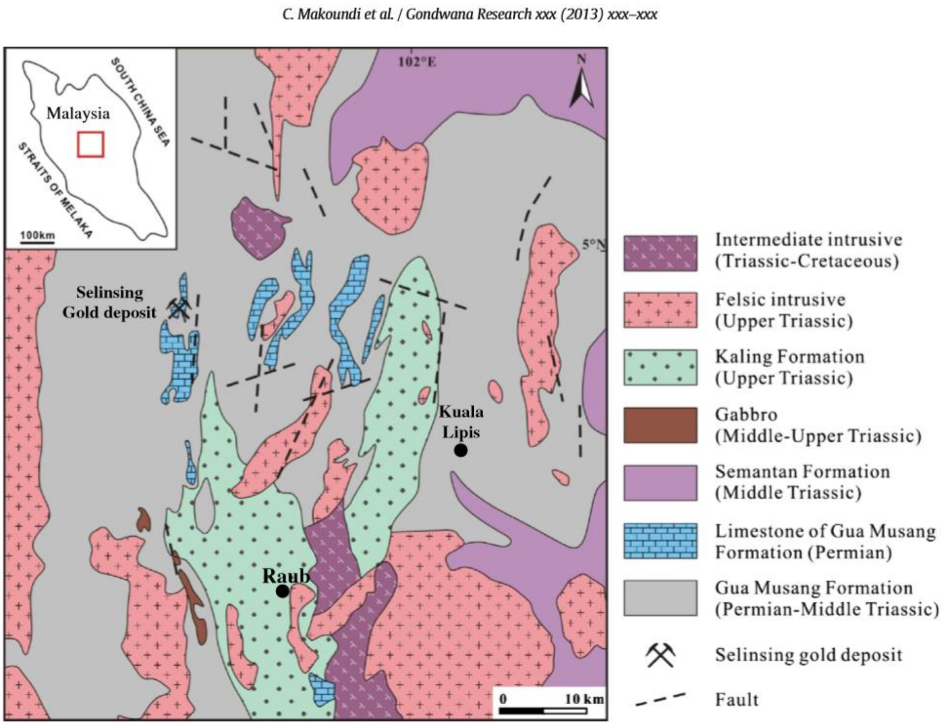

Figure 2.3: Deposit-scale geology of the Selinsing gold deposit, Malaysia (Makoundi, 2012).

2.3 Gold Mineralogy

Mineralogy is the branch of science which deals with the physical and chemical properties of the minerals like their crystal structure, hardness, luster, optical and the ways of distinguishing them. Commonly, gold ore are classified into either free milling or refractory ores. If the recovery is more than 90%, the ore is considered as free-milling ore. In the same way, a refractory ore is considered if the material gives low recovery by cyanidation and some extra process will be required to enhance the process performance (Zhou, Jago and Martin, 2004). Based on the mineralogical characteristics and mineral processing techniques required, gold ores can be classified into 11 types as shown in Table 2.1.

Table 2.1: Types of gold ore. Modified after (Zhou, Jago and Martin, 2004).

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

2.3.1 Gold ores and minerals

According to (Harris, 1990) at present, there are twenty-six accepted gold-containing minerals, three unpublished new mineral species, two doubtful species and thirteen unnamed compounds. The most important gold mineral is native gold and its varieties as the result of metal substitutions. Pure gold is very rare in nature. Table 2.2 list all gold minerals along with their composition.

Table 2.2: Gold minerals. Modified after (Zhou, Jago and Martin, 2004)

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

(Zhou, Jago and Martin, 2004) classified gold according to the mode of occurrence, into three categories: microscopic gold, submicroscopic gold and surface-bound gold as shown in Table 2.3. Gold minerals are defined as the minerals in which gold is present as a main constituent (e.g. native gold and electrum). Gold carriers are defined as both the gold mineral and the mineral in or on which gold occurs only in trace amount (such as pyrite and arsenopyrite).

Table 2.3: Classification of gold by forms and carriers. Modified from (Zhou, Jago and Martin, 2004)

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

Microscopic gold, also known as visible gold, comprises gold alloys, gold tellurides, gold sulfides, gold selenides, gold sulfotellurides and gold sulfoselenides etc. Native gold (Au) and electrum (Au, Ag), found in various types of gold deposits, are the two most common and most important gold minerals. Other gold minerals of economic significance in some gold deposits include kustelite (AgAu), auricupride (Cu Au) tetraauricupride (CuAu), calaverite (AuTe3), krennerite ((Au,Ag)Te2), aurostibite(AuSb) and maldonite (Au2Bi). Microscopic gold in primary ores occurs as pristine grains of varied size and shape in fractures and microfractures, or as attachments to and inclusions in other minerals.

Gold that is invisible under optical microscope and scanning electron microscope is referred as submicroscopic gold or invisible gold. Gold usually occurs in these ores as discrete particulates (<0.1 μm in diameter) within sulfide minerals (mainly in pyrite and arsenopyrite) Surface-bound gold is the gold that was adsorbed onto the surface of other minerals during the mineralization and subsequent oxidation or metallurgical processing. (Zhou, Jago and Martin, 2004).

2.3.2 Characterization of gold

Characterization process of gold includes both physical and chemical assessments combined to understand the mineralogy of the gold ore. This enable the mineral composition and the associated mineral of the ore to be identified. The most efficient gold extraction processing route is directly related to the inherent mineralogical features of the gold ore being processed. The mineral composition determines the performance of all chemical and physical processes involved in gold extraction (Chryssoulis and Cabri, 1990). It is therefore crucial to accurately characterize the mineralogical nature of the ore to be processed; i.e. characterization of the precious metal phases (gold deportment) and gangue minerals. (Coetzee *et al.*, 2011).

As the free-milling gold ores are becoming scarce and more refractory ores are being discovered and processed, gold process mineralogy receives more and more attention from both the mineralogist and metallurgist as it helps to solve various problems encountered during gold ore processing. Steadily rising gold prices are also stimulating the need for gold process mineralogy due to the increasing demand for and production of the yellow metal (Zhou, Jago and Martin, 2004). Therefore, it is crucial to understand the mineralogy of the ores to be processed. Understanding of the mineralogy of the ores also helps in reducing the overall processing cost, making it more profitable by avoiding unnecessary process and enable the optimization of the amount of reagents used during the process. As a result, proper processing flowchart which are able to obtain good gold recoveries can be designed based on the result of the characterization of the specific complex gold ores.

Characterization involved various process and testwork to be done on the ore samples. There are various characterization techniques being employed together with the technology advancement. Combination of mineralogical and metallurgical test work is found to provide the most cost and time efficient means to fully characterize gold bearing samples (Zhou, Jago and Martin, 2004). In this study several techniques were employed to characterize the ore samples such as mineralogical study via XRF and XRD analysis, gold assay using Fire assay and direct cyanidation and microscopic study by the means of optical microscope and FESEM/EDX.

2.4 Process Mineralogy

Process mineralogy has come into its own as a respected inter-discipline in the fields of mineralogy and metallurgy - a subject that occupies an important place in both research and industry. Process mineralogy helps address issues and problems related to gold ore processing. It provides useful information on process selection, flowsheet development, recovery improvement and reagent utilization improvement. By joining classic mineralogical methods, current instrumental analysis and diagnostic metallurgy, the mineralogist is able to balance the various types of gold occurrence in an ore (Zhou, Jago and Martin, 2004).

2.4.1 Mineral Composition

X-Ray Fluorescence (XRF) and X-Ray diffraction (XRD) are among the common analysis applied in determining the mineral composition of the gold ore sample. In X-ray fluorescence spectroscopy, the process begins by exposing the sample to a source of x-rays. As these high energy photons strike the sample, they tend to knock electrons out of their orbits around the nuclei of the atoms that make up the sample. When this occurs, an electron from an outer orbit, or "shell", of the atom will fall into the shell of the missing electron. Since outer shell electrons are more energetic than inner shell electrons, the relocated electron has an excess of energy that is expended as an x-ray fluorescence photon. This fluorescence is unique to the composition of the sample. The detector collects this spectrum and converts them to electrical impulses that are proportional to the energies of the various x-rays in the sample's spectrum. XRF data gives information regarding the elements present inside the sample without indicating what phases they exists.

The principle of XRD is standard guide to determine the phase analysis. When a monochromatic x-ray beam with wavelength is incident on the lattice planes in a crystal planes in a crystal at an angle, diffraction occurs only when the distance travelled by the rays reflected from successive planes differs by a complete number n of wavelengths. By varying the angle, the Bragg's Law conditions are satisfied by different d-spacing in polycrystalline materials. Plotting the angular positions and intensities of the resultant diffraction peaks produces a pattern which is characterised of the sample. Where a mixture of different phases is present, the diffractogram is formed by addition of the individual patterns.

2.4.2 Fire Assay

Fire assay is the most common method applied in many study regarding gold characterization. It has been proven to very reliable to determine precious metal content and has become one of fundamental component process mineralogy. Fire assay provides bulk gold content inside the sample, complementing the mineralogical information obtained from other methods. Fire assaying is the traditional method of gold analysis and can measure gold concentrations from 0.001 to >50 g/t (Zhou, Jago and Martin, 2004).

(Raw, 1997) states that when the mixture fired inside the furnace with high temperature ranging from 1000 ºC to 1200 ºC, the precious metal does not oxidise, unlike base metal. After a duration of 1 hour, the fusion occurred and the molten is poured into a mould and left at room temperature to let it cool down. The slag that separate the impurities inside the mixture need to be removed and the lead button formed at the bottom contain gold and other precious metals which form Au-Ag-Pb alloy is collected (Huffman, Clark and Yeager, 1999).

The slag then is removed and the lead button is placed in the cupel that made from bone ash. The bead later fired inside the furnace at 1000 ºC for 1 hour. This process is known as cupellation process in which the cupel will absorb the lead, leaving behind a bead, known as silver prill that contain gold and some of platinum group elements (Hoffman, Clark and Yeager, 1998).

The process parting which means dissolving the bead in nitric acid is conducted and leaving behind a bead which can be weighed as gravimetric finish (Hoffman, Clark and Yeager, 1998). Another possible method was by dissolving the entire bead in the acid (Aqua Regia) and determine the gold content by using Atomic Absorption Spectroscopy (AAS) (Hoffman, Clark and Yeager, 1998)

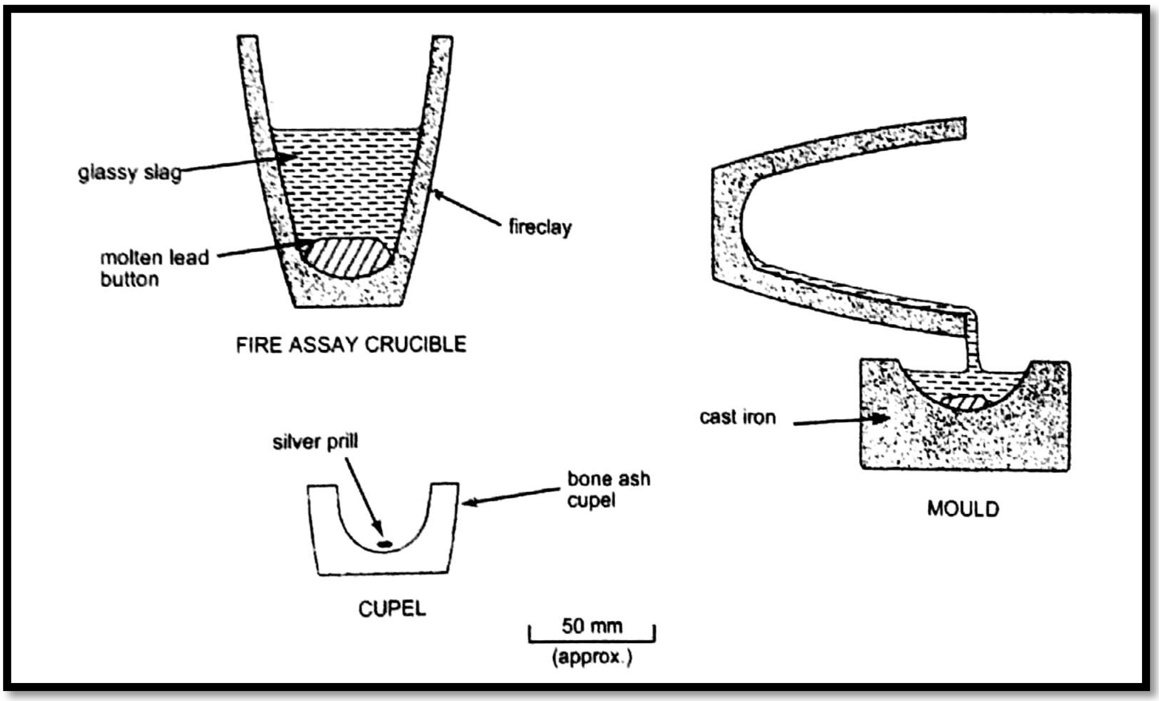

Figure 2.4: Fire Assay method

In reserve estimation, it is common practice to reduce the sample size to one assays tonne for analysis, although large and small amounts are used in certain cases. The basic procedure for fire assay involves mixing an aliquot of powdered sample (10g, 15g, 30g, or 50g are the common size used) with soda ash (calcium carbonate), borax (Sodium borax), litharge (PbO), flour (baking flour used to add carbon as reductant), Silica and possible nitrate (potassium nitrate). To this mixture, Ag or Pd as a collector can be added in solution (Huffman, Clark and Yeager, 1999).

2.4.3 Direct Cyanidation

Direct cyanidation is often applied to determine maximum amount of recoverable gold by cyanidation (Zhou, Jago and Martin, 2004). According to (Marsden, 1992) the gold is extracted by converting the gold to water soluble aurocyanide metallic complex ions. The dissolved gold is usually recovered by the Carbon-in-Leach (CIL) or Carbon-in-Pulp (CIP) process. It can be used to quantify the gold that can be extracted via direct cyanidation i.e the free mill gold. Free mill gold is the gold particles that is free and exposed gold which has been liberated through milling process and cyanide are able to reach and leach the gold.

Comprehensive coverage of the chemistry of the cyanidation process was provided by Finkelstein and Barsky. They all agree that the overall dissolution of gold in dilute cyanide solutions may be represented by the classic Elsner's equation:

$$4Au + 8CN^{-} + O_2 + 2H_2O = 4Au(CN)^{-} + 4OH^{-}$$

$$2Au + 4CN^{-} + O_2 + 2H_2O = 2Au(CN)^{-} + 2OH^{-} + H_2O_2$$

$$2Au + 4CN^{-} + H_2O_2 = 2Au(CN)_2 + 4OH^{-}$$

The above reactions clearly indicate that the leaching mechanism involved in the cyanidation process is electrochemical in nature as was initially postulated by Kudryk and Kellog. As shown in the above equations, dissolved oxygen is an essential ingredient in the cyanide leaching step.

The rate of gold dissolution appears to peak about 85ºC, as an optimum compromise between oxygen content of the solution and its activity. However, heating of the leach pulp is not considered practical due to cost of heating and increased consumption of cyanide through decomposition and reaction with cyanicides. Cyanicides are those substances found in ores, concentrates and tailings which cause a loss of CN ions from the leach solution and thus result in excessive consumption of cyanide.

2.5 Factors affecting gold recovery

Most gold ore processing involve conventional gravity separation and cyanidation. Ores which are not amenable to direct cyanidation or difficult to process are classified as refractory ores. This type of ore required comprehensive mineralogical investigations to increase the gold recovery. On the other hand, gold which give high recoveries to cyanide leaching are classified as free-milling ores. Usually, there is no single cause for poor gold extraction but rather a combination of range of causes. Previously, there are several factors affecting gold recovery which had been discussed by (Harris, 1990), (Gasparrini, 1983) and (Coetzee *et al.*, 2011). Common factors are discussed briefly in the next subsequent sub-topic and there may be other factors which are not highlighted in this paper.

2.5.1 Poor Gold Grain Exposure

The grain size of gold bearing minerals varied from visible like gold nugget to those invisible by naked eye like microscopic gold. The grain exposure to leaching solution is a vital factor in leaching process for the gold recovery. Exposed gold grain can directly be leached as it comes into contact with the cyanide solution while unexposed gold grain require longer retention time. Very fine (normally <10 µm in size) particulate gold, locked in sulphide or other gangue, may not be exposed to cyanide solutions at ‘‘normal” grinds (e.g. 80% passing 75 µm). This may require finer to ultra-fine grinding (e.g. 80% passing 20 µm or 80% passing 10 µm) to expose the particulate gold. Ultra-fine grinding is a physical method for the liberation of locked gold, but due to high energy consumptions it is an expensive option. If the ultra-fine particulate gold restricted to sulphides, upgrading by floatation/gravity and oxidative destruction of the sulphides by roasting, pressure oxidation or bio-oxidation could be possible processing options (Coetzee *et al.*, 2011).

2.5.2 Associated sulphide minerals

The sulfide minerals are important as they always act as the host mineral for the gold and also some sulphide minerals like pyrrhotite and marcasite are attacked by and have the effect of fouling the cyanide solutions, whereas chalcopyrite and other copper sulfides cause abnormally high cyanide utilization and thus deplete that required to dissolve gold. The two most common sulfide host minerals are pyrite and arsenopyrite (Harris, 1990).

2.5.3 Gangue mineralogy

Different ores have different type of gangue minerals present. Not only do the gangue minerals have an effect on the grinding characteristics, but they are important in defining the performance of cyanidation. Hence, it is vital to understand the mineralogy of the gangue minerals as it have effect in the processing of gold ores (Harris, 1990). Emphasis is placed on the identification and quantification of deleterious components such as cyanide and oxygen consumers, preg-robbers and also other minerals that would pose difficulties during processing (such as natural floaters and clay minerals) (Coetzee *et al.*, 2011).

2.5.2 Coating on gold

Coatings on gold, formed either by supergene alteration of the deposit or introduced during the processing of the ore can have detrimental effect on the gold recovery. These coatings can usually involved iron oxides, silver chlorides and antimony, manganese and lead compounds. The coating will inhibit the cyanidation process to react completely. The source of the coating need to be investigated to prevent low recovery.

2.5.3 Cyanide and oxygen consumers

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

Oxygen is one of the reagents consumed during cyanidation, and insufficiency of dissolved oxygen in the leach solution will mitigate the cyanidation reaction. Oxygen consumers, such as pyrrhotite and marcasite, can have a negative effect on cyanidation. The oxidation state of the leach, and a need for oxygen addition, should then be meticulously monitored to optimize the leach performance. Pre-oxidation is a common step, where oxygen consumers are ample. Air or pure oxygen gas can be bubbled through the pulp to increase the dissolved oxygen concentration (Coetzee *et al.*, 2011).