CHARACTERIZATION AND PROCESS RECOVERY OF REFRACTORY GOLD ORES FROM CENTRAL BELT MALAYSIA

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CHARACTERIZATION AND PROCESS RECOVERY OF REFRACTORY GOLD ORES FROM CENTRAL BELT MALAYSIA

by

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LIST OF SYMBOLS

%	Percentage
&	Ampersand
λ	Lambda
θ	Theta
µm	Micron meter
Å	Angstrom
Au	Gold
cm	Centimeter
CuFeS	Chalcopyrite
D_{50}	Mid-point in size distribution of particles passed through
D_{80}	80% of particles passed in size distribution
FeAsS	Arsenopyrite
FeS_2	Pyrite
g	Gram
g/mol	Gram per mole
g/t	Gram per ton
h	Hour
kg	Kilogram
kV	Kilo-Voltage
m	Metter
mm	Millimeter
nm	Nanometer
^{o}	Degree

^{o}C	Degree Celsius
$^{o}C/min$	Degree Celsius per minute
rpm	Run per minute
PbS	Galena
pm	Picometer
ppb	Part per billion
ppm	Part per million
Sb_2S_3	Stibnite
wt (%)	Weight percentage
ZnS	Sphalerite

LIST OF ABBREVIATIONS

AMD	Acid Mine Drainage
Apy	Arsenopyrite
BSE	Back Scatted Electron image
C	Concentrate
Ccy	Chalcopyrite
EDX	Energy Dispersive X-ray analysis
Gn	Galena
LOI	Loss on Ignition
pH	Potential of Hydrogen
Py	Pyrite
Qtz	Quartz
SEM	Scanning Electron Microscope
S-G8	Selinsing Group 8
S-G9	Selinsing Group 9
Sp	Sphalerite
S-Stockpile	Selinsing Stockpile sample
Stb	Stibnite
T	Tailing
XRD	X-ray Diffraction
XRF	X-ray Fluoresce

PENCIRIAN DAN PROSES PEROLEHAN BIJIH EMAS REFRAKTORI DARIPADA JALUR TENGAH MALAYSIA

ABSTRAK

Pemineralan emas di Jalur Tengah Malaysia wujud bersama metasedimen peringkat rendah kawasan gunung berapi. Hubungkait di antara silikat dan sulfida di kawasan ini adalah sangat rumit. Justeru, pencirian emas dan proses pra-pengkonsentratan (pengkonsentratan secara gravity dan pengapungan buih) adalah sangat penting supaya sebahagian besar mineral reja dan amaun bahan kimia yang akan digunakan dapat dikurangkan dalam proses-proses seterusnya. Kajian yang dijalankan ke atas sampel S-Stocpile, SG-8 and SG-9 mendapati ia mengandungi terutamanya mineral kuartza dan mineral sulfida, seperti stibnit, pirit, arsenopirit dan galena. Emas ditemui sebagai "emas boleh dilihat" dan "emas tidak boleh dilihat". Emas terkisar bebas dijumpai terutamanya dalam sampel S-Stockpile daripada yang bersaiz halus senhingga bersaiz kasar (100µm). Bagi sampel S-G8 dan sampel S-G9 emas didapati wujud sebagai emas terkisar bebas yang halus, terkurung dan inklusi serta bendalir pepejal terutamanya dalam mineral sulfida seperti, stibnit, pirit, arsenopirit dan galena. Pra-pengkonsentratan secara mendulang ke atas sampel S-Stokpile yang berbeza saiz (-1.25 mm) dan (-100 µm) didapati tidak membantu dalam peningkatan gred emas kerana partikel emas halus dan berbentuk nipis keluar daripada dulang semasa proses mendulang. Walau bagaimanapun, pra- pengkonsentratan dengan kaedah pengapungan buih ke atas sampel S-G8 dan S-G9 dengan mengguna 100, 200, and 300g/t bahan pengumpul Aerofloat 208 dan Aerophine 3418A promoters menunjukkan emas terkurung bersama mineral sulfida boleh diapungkan pada pH 4, 6, dan 8. Terdapat peratusan kecil emas terkisar bebas terapung bersama konsentrat disebabkan oleh kesan pemerangkapan. Secara amnya bahan pengumpul Aerophine 3418A adalah lebih berkeupayaan untuk mengapungkan mineral sulfida berbanding dengan Aerofloat 208 terutamanya pada pH 6 dengan dos bahan pengumpul 200 g/t.

CHARACTERIZATION AND PROCESS RECOVERY OF REFRACTORY GOLD ORES FROM CENTRAL BELT MALAYSIA

ABSTRACT

Gold mineralization in Central Belt, Malaysia, occurred along with a low grade metasedimentary volcanic terrain. The relationship between silicate and sulfide in this area is complicated. Therefore, gold characterization and pre-concentration processes (gravity concentration and froth flotation) are very important since it can reduce the amount of gangue minerals and the chemical consumption in further processes. Studies on S-Stockpile, S-G8 and S-G9 samples show that they contain mainly quartz and sulfide minerals such as stibnite, pyrite, arsenopyrite, and galena. Gold was found in both as “visible gold” and “invisible gold”. Free milling gold was mostly identified in S-Stockpile sample from fine to coarse grain (about 100µm). In S-G8 and S-G9 samples gold particles were observed as fine free milling form, interlocking and also as inclusion or as solid solution in sulfide minerals, mainly stibnite, pyrite, arsenopyrite, and galena. Panning of S-Stockpile sample with two different sizes (-1.25mm) and (-100µm) do not help in upgrading the gold due to fine and flaky in shape of gold particles were floated out of the pan. However, the pre-concentration by froth flotation of S-G8 and S-G9 samples by using 100, 200, and 300g/t of Aerofloat 208 or Aerophine 3418A promoters were able to recover the gold interlocking in sulfide minerals at pH 4, 6, and 8. Certain percentage of free milling gold particle was also floated to the concentrate due to the entrainment. Comparatively, Aerophine 3418A promoter had stronger in gold and sulfide recovery than Aerofloat 208 promoter, especially at pH 6 with a dosage of 200g/t.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Gold is an important resource to economy, and it has been used worldwide as coins, jewelry, art objects, and in electronic applications. In the ancient times, the principal gold-producing country was Egypt (Yalcin & Kelebek, 2011; Kesler & Simon, 2015; and Adams, 2016). It generally occurs in various forms such as native, electrum, and gold alloy, but some is commonly present as “invisible” gold or as gold tellurides, gold selenides and gold sulfides (Petruk, 2000). Besides native or free gold, it is also commonly found associated with sulfide minerals such as pyrite, arsenopyrite, galena, sphalerite, chalcopyrite, pyrrhotite, and tennantite-tetrahedrite (Petruk, 2000; Ariffin, 2012; and Adams, 2016).

Gold ores are found in different types, which can be classified as refractory, complex and free milling gold ore based on the mineral characteristics and mineral processing technique requirements (La Brooy et al., 1994). Refractory gold ore is complicated occurrence mainly in sulfide ore, and some parts were interlocked in sulfide minerals such as arsenian pyrite and arsenopyrite (ultrafine gold), and stibnite (Chen et al., 2002; Vaughan, 2004; and Millard, 2005), and they do not provide economic gold recovery with conventional cyanidation (La Brooy et al., 1994, and Zhou et al., 2004). However, complex ore occurring in various geological environments, especially copper-gold deposit, can give acceptable economic gold recovery only with the use of significant reagents or more complex pre-treatment processes. Despite, free milling gold ore is that gold particles are completely liberated at 75µm of 80% passing, and the gold recovery can be achieved up to 90% (La Brooy et al., 1994; Zhou et al., 2004; and Vaughan, 2004).

Malaysia is a country rich of gold deposits, especially in Peninsular. Gold production in Malaysia has come widely from the Central Main Range region of Peninsular Malaysia covering the states of Pahang, Terengganu and Kelantan. The majority of gold production in Central Belt are Berching-Chinong, Ulu Sokor, Ketok Batu, Selinsing Gold Manager, Tui, Penjom, Tersang, Raub, Pason, Kanan Kerbau and Batu Bersawah, and they can provide desirable gold production (Yeap, 1993; Ariffin & Hewson, 2007; and Ariffin, 2012). Selinsing Gold Manager and the Pejom gold mine in Pahang were the major gold producer to lead Malaysia's economy due to its high price and popularity (Pui-Kwan, 2013).

Gold mineralization in Central gold belt occurred as a low grade meta sedimentary volcanic terrain, and this belt can be classified into two types: type I (gold belt 2) and type II (gold belt 3), as shown in Figure 1.1. The type I belt mineralization is identified as the gold geochemical zone which provides two majors goldfields, the Buffalo Reef (Kanan Kerbau) and further south, the Selinsing Gold Manager and the Tersang alluvial goldfield (Yeap, 1993). However, the type II mostly occurred as marine classic sediments, intermediate to acid volcaniclastics, and subordinate rhyolitic lava sequences, like Penjom gold mine. The type II mineralization belt is gold bearing with galena-tetraherite-tellurides ore, gold bearing with arsenopyrite and pyrite, and gold bearing pyrite (Ariffin, 2012). The Selinsing Gold Manager deposit is hosted by meta-sedimentary units (Yeap, 1993; and Makoundi et al., 2014).

Pui-Kwan (2013) stated that there were more than 10 operating gold mines in Malaysia, as highlighted in Figure 1.1, which were located in the States of Kelantan, Pahang, and Terengganu, and more than 90% of gold in Malaysia was mined was from many areas in Pahang, such as Penjom gold mine in Penjom, the Selinsing Gold

Manager in Sungai Koyan, and Raub gold mine in Raub, and they were the main role to lead the country's economy.

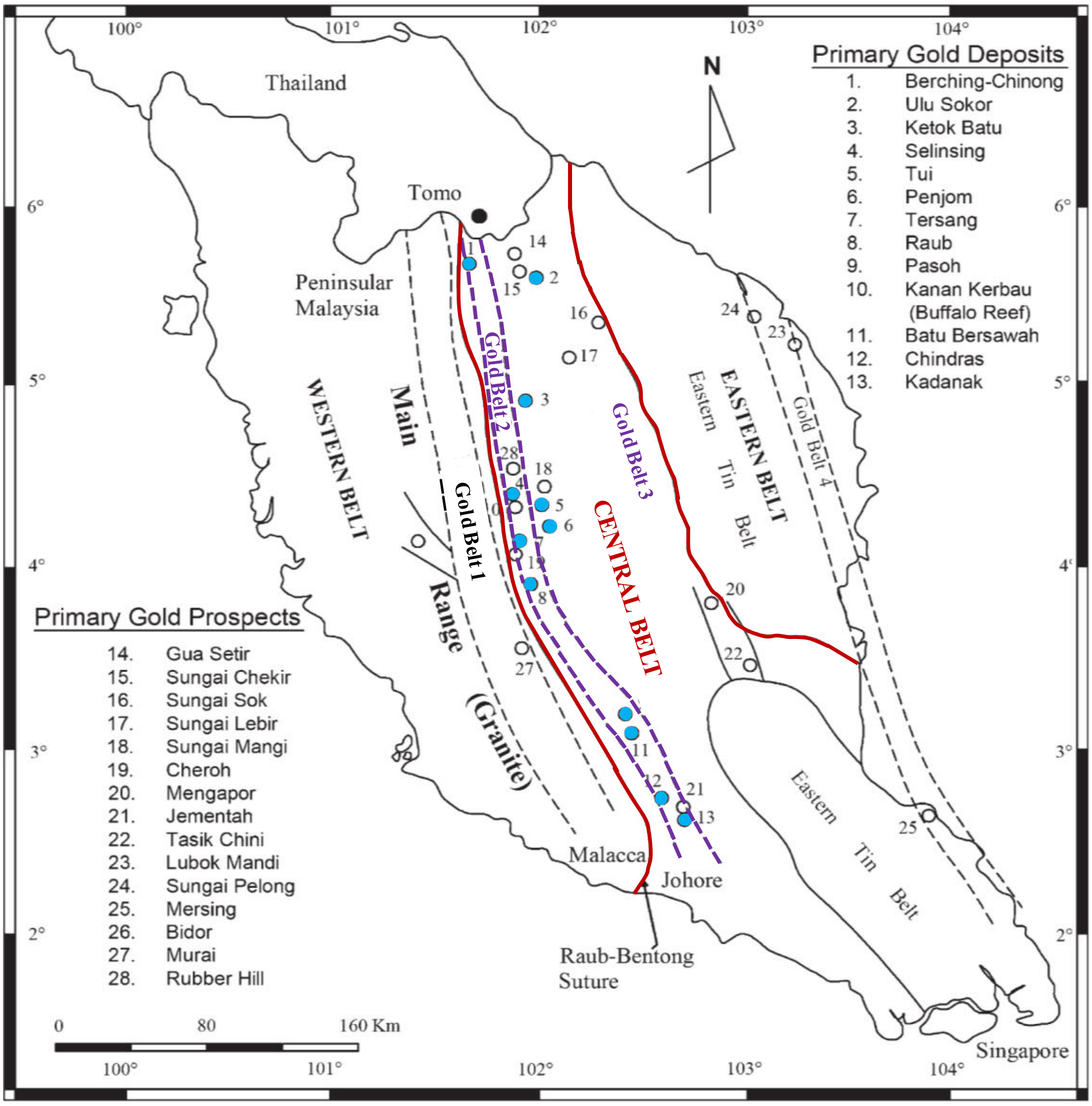

Figure 1.1: Primary gold deposit in Peninsular Malaysia, modified from (Yeap, 1993)

1.2 Problem Statement

Gold mineralization in the Central Belt associated mainly with hydrothermal quartz vein system including skarn and volcanogenic massive sulfides which are commonly arsenopyrite, pyrite, galena and sphalerite, and the origin of gold was come from volcanic exhalative during volcanic activity in the Permian to Triassic (Ariffin, 2012; and Li et al., 2015). Anyway, the mineralization in those areas are still uncertain in the researcher's understanding, and gold resources cannot be used directly from mine sites due to the impurities, especially sulfide gold ore (Adams, 2016). The relationship between the gold mineralization of sulfide ore and silicification is so complicated, thus the mineral characterization of gold ore needs to be well carried out before starting with the recovery processes.

The presences of fine gold particles are frequently found in sulfide refractory gold ore. The major problems of these types of ores are very fine gold disseminated or a high degree of interlocking within sulfide minerals inside the massive bodies of pyrite, pyrrhotite, arsenian pyrite, stibnite and arsenopyrite which mostly associated with silicate gangue minerals. In addition, graphite, carbonaceous materials, secondary copper minerals (malachite, covellite, chalcocite, azurite, brochantite, etc.), bomite, enargite, marcasite, and pyrrhotite can cause problems to the processing (Leja, 1982; Teague et al., 1999; Petruk, 2000; and Millard, 2005). In general, the recovery of refractory gold follows the same trend as the sulfide minerals. The most significant of sulfidic refractory gold appears to be hosted by the pyrite, arsenopyrite, and stibnite components of ore are amenable to flotation recovery (Teague et al., 1999; Millard, 2005; and Badri & Zamankhan, 2013). Pre-concentrate of refractory sulfide gold ore is very important before further processes because it can reduce some amount of gangue minerals, some toxicity of materials, and reagents consumption (Allan & Woodcock, 2001).

Normally the extraction gold ore is extracted by cyanide leaching process, however the extraction of gold from such a refractory gold is hard to get a satisfied recovery by this process under many conditions. The dissatisfactory recovery was due to the contents of arsenopyrite, pyrite bearing gold and carbonaceous matter contained in refractory ores (Senanayake, 2008; and Millard, 2005). Furthermore, the environmental issue of cyanidation may cause toxicities which come from the tailing pond in case it is not properly designed, especially in the rainy season. The toxicity of the trace elements bearing sulfide mineral by cyanidation such as lead, arsenic and its compound, antimony, mercury, cadmium, bismuth, selenium, and tellurium are classified as harmful elements. For instance, lead (II) which is the element of galena has a very low solubility under gold cyanidation condition forming with insoluble hydroxide. It is a heavy metal that is very toxic to human, plants and animals to cause cancer (Graeme & Pollack, 1998; Donato et al., 2007; and Kyle et al., 2011).Stibnite, pyrite and arsenopyrite are the most common minerals associated with gold, yet they can occur in solution at very high concentrations as oxy- or hydroxy-in alkaline water which extremely effected to the environment (Kyle et al., 2011). Particularly, Mother Nature Cambodia NGO released a report in 2018 that 17 people were killed by using river water contaminated by cyanide during raining season. Due to the harmful of cyanide to the environments, cyanide leaching was banned in gold mining and processing in Czech Republic.

Yalcin & Kelebek (2011) in their work found that froth flotation was successfully recovered gold by xanthate promoter in trend of gold carried sulfide minerals in the particle size ranged from 53 to 205 µm, and gold was formed as native inclusion in pyrite, and along the boundary between pyrite and non-sulfide minerals. Through the operation, gold could be recovered more than 90%. Therefore, froth flotation is the promising technique to pre-treatment the complex and medium refractory gold ores.

1.3 Objective of Study

The aims of this research works are:

(i) To characterize mineralogy, physical property, and geochemical of gold ore samples from the Selinsing Gold Manager

(ii) To study the possibility of pre-concentrate of gold ore samples by gravity method (panning)

(iii) To evaluate the gold froth flotation process at various parameters using two types of collectors.

1.4 Scope of Research

This research is divided into two main parts. First of all, gold ore samples were collected and received from Selinsing Gold Manager. The characterization of raw materials such as the mineralogical characteristics, the identification of gold-bearing minerals, the proportion of gold occurring in minerals (e.g. native gold, electrum, gold alloy), the identification of associated metallic and non-metallic minerals, and the proportion of gold occurring as “invisible” gold in other minerals, is determined by using microscope, XRD, XRF and BSE-SEM/EDX analyses. Second part is the pretreatment of the ore sample by gravity concentration (panning) and by froth flotation method by controlling the pH (4, 6, and 8), dosage of collectors (100, 200, and 300g/t), and types of collectors (Aerofloat 208 and Aerophine 3418A promoters).

1.5 Thesis Outline

In order to present this research work, this thesis is divided into five chapters which were briefly described and discussed as follows:

Chapter 1 begins with general introduction of the research background including type of gold ores, gold production in Malaysia, and its advantages. The problem statement, the objectives of study and scope of research are particularly pointed out.

Chapter 2 covers the various literature reviews of geological occurrence of gold, gold mineralogy, gold classification, physical and chemical properties of gold, some information of gold usage and gold production, gold mining techniques which are currently operating, and gold recovery process with some fundamental concepts.

Chapter 3 comprehensively describes the raw materials specification, sample preparation, and research methodology to characterize the properties of gold ores samples, and pretreatment process by using gravity concentration method (panning) and froth flotation.

Chapter 4 refers to the results and discussion of all data to characterize gold ores compositions, and to discuss about gold recovery by using panning and froth flotation. Based on the data, the observation presented in graphs, tables, and figures are discussed.

Chapter 5 concludes the obtained results from this research work, and it presented together with the suggestion for the most effective methods for the further research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, it includes literature reviews on gold deposits, gold mineralogy, gold formation and gold mining technology, which are the significations to access the recovery process. Further, the information of some gold processing techniques is stated, such as physical and chemical processing.

2.2 Geological Occurrence of Gold/ Gold Deposits

Gold ore is found in different types, and it is considered as a rare metal with approximately 3ppb in the earth's crust (Boyle, 1979). The gold deposits present in both oceanic and continental volcanic arc. In geological setting of gold deposits, gold was transported and concentrated by magmatic, hydrothermal and sedimentary process (Frimmel, 2008). Although it has been come up with many methodes, there are more than 10 million tonnes of gold that does not have yet commerciallized from the oceans (Kesler & Simon, 2015). There is only 7×10^{-7} of total gold concentrate in known ore body which is found in the total amount of gold available in continental crust (Frimmel, 2008). The source of gold in these types is in magma and related magmatic fluids which are typically derived from the partial melting of lithospheric mantle above subduction zone (Kesler & Simon, 2015). The average concentrate grade of gold in the earth's crust is about 0.005g/t which is really lower than other metals such as silver and copper which are 0.07g/t and 50g/t, respectively (Marsden & House, 2006).

Figure 2.1 illustrates the lithosphere-scale environments for the principle gold deposit types classified according to the host rock or genetic model, of hydrothermal veins deposits, such as volcanogenic massive sulfide, porphyry Cu-Au, epithermal and intrusion related Au, and placer deposits/ alluvial deposits (Groves et al., 2005; and Rusk et al., 2008). Kesler & Simon (2015) however divided the gold deposits into three types hydrothermal veins deposits (lode gold deposits or intrusive deposits), placer deposits (alluvial deposits) and disseminated deposits which is the gold occurred with a variety of geologic environments (a wide variety in the thickness, grade, chemistry and ore mineralogy), commonly in volcanic and sedimentary rocks. There are only placer and hydrothermal gold deposits have which provided high production of gold.

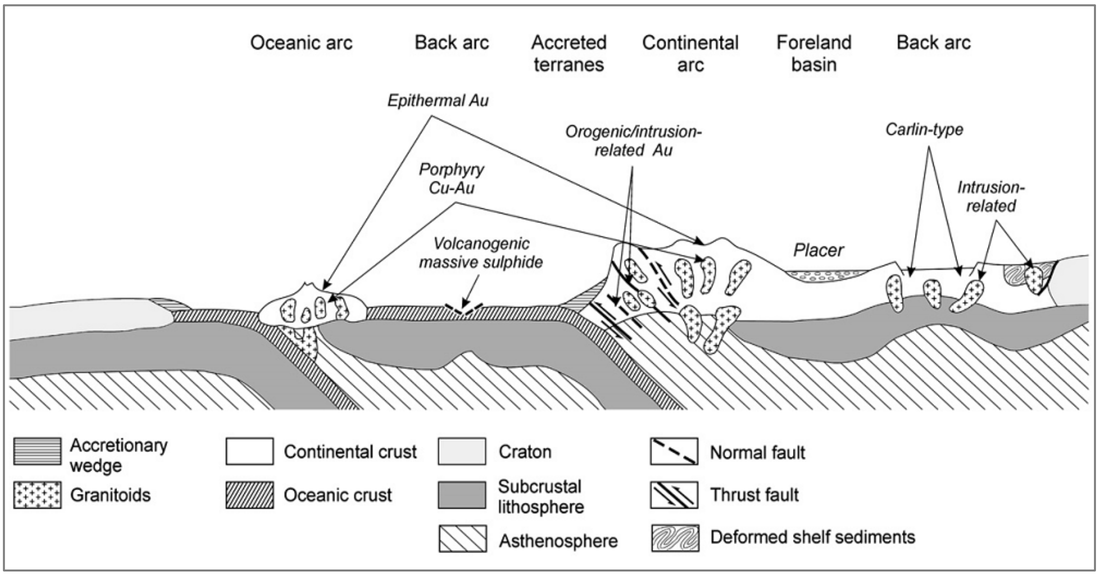

Figure 2.1: The principle types of gold deposits (Groves et al., 2005)

The wide variety of deposits include gold quartz veins, gold sulfide veins with varying amounts of quartz, calcite or other gangues, epithermal veins and breccia pipe (Kesler & Simon, 2015). Even so, the presence of gold is usually found in the quartz-carbonate vein with a sulfide content and as a gold-bearing-ankerite-quartz intrusive rock (Chye et al., 2001; and Endut et al., 2015). Gold occurred in hydrothermal mineral that associated with quartz veins becomes concentrated in alluvial sands as a placer deposit due to its very high specific gravity during sedimentary processes (Pellant & Pellant, 2014). In addition, the high amount of gold has been found in porphyry copper deposits in the upper crust which are the vital potential sources for gold in lower temperature epithermal deposits. Gold is found in porphyry copper deposits in formed of solid solution in Cu-Fe, and also as fine native gold gain Gold deposited in composed of limestone, and is hosted by pyrite and arsenopyrite, and breccia type ore, which tellurides are the main gold carriers (Xu et al., 2014).

The timing of gold mineralization is highly restricted to greenschist facies of brittle-ductile syn-deformation structures (sheared zone of structurally-hosted lode-gold). It is hosted in sheared zone folded and contact metamorphosed volcanic, volcanoclastic and sedimentary sequences (Rusk et al., 2008; Kesler & Simon, 2015; and Tshibubudze & Hein, 2016). The gold mineralization in Ajmal mine, Pahang Malaysia was found that quartz veins as parallel veins in shear zone. Native gold is fine grain, and it is found as gold bearing veins as sulfide-poor associated with tertrahedrite and some galena, chalcopyrite and sphalerite and petzite. The wall rock alteration is visible and associated with silicification. The mineral deposit occurred at low temperature and was far from the sources (Hassan, 2008).

The majority of the sampling problems which associated with precious metal deposits are generally found in hydrothermal veins and breccia zones (Kesler & Simon, 2015). Placer gold deposits are easily liberated for the processing as a result of its size, normally from 50μm to 100μm (Zhou et al., 2004), and they have supplied about 43% of total world gold (Frimmel, 2008). The grade of gold depends on the types of deposits. For instance, volcanic massive sulfide deposits contain gold from 1g/t to 7g/t (Petruk, 2000).

2.3 Gold Mineralogy

The mineralogy and particle size distribution of gold are the best clues for selecting the best mineral processing method for gold recovering. The gold particle size can vary from large nuggets to very fine grain which locked inside other minerals typically inside sulfide or quartz matrix, and those minerals should be liberated from 50% to 80% smaller than 75µm (O'Connor & Dunne, 1994; and Marsden & House, 2006).

Gold generally occurs as native, electrum and gold alloy, but some commonly present as "invisible" gold and some as gold tellurides, gold selenides and gold sulfides. It is associated with specific ore or gangue minerals, and some may cause processing problems. The native gold, electrum, and gold alloy for a solid solution series have similar physical properties and appearances (Petruk, 200; Marsden & House, 2006; and Kesler & Simon, 2015). Native gold comprises Au up to 99.8%, but it is mostly found between 85 and 95% with impurity mainly silver. However, when silver contained in gold as gold-silver alloy over 20% (between 25% and 55%), in the gold ore, named as electrum (Marsden & House, 2006). Invisible gold occurs in numerous sulfides, mostly arsenian pyrite, chalcopyrite and stibnite, with fine grain size of metallic gold (Chen et al., 2002; Millard, 2005; and Marsden & House, 2006).

The gold mineralization can be classified into three types (Chye et al., Ariffin & Hewson, 2007). Firstly, gold occurs in sheet and stockworks quartz -carbonate and tourmaline veins carrying significant amount of sulfide like pyrite, arsenopyrite, and trace of pyrrhotite, galena and hematite (Ariffin & Hewson, 2007; and Tshibubudze & Hein, 2016). For instance, the sulfide gold ore in Chertovo Koryto, Russia, was associated with pyrrhotite and arsenopyrite with very minor pyrite, while pyrite is the predominant sulfide in Sukhoi Log ore (Yudovskaya et al., 2016). Secondly, gold disseminated within stockwork of quartz-carbonate veins affiliated with tonalite and with graphite-ankerite-quartz intrusive rock (Ariffin & Hewson, 2007), and gold was complicated occurrence as very fine grain size which is associated with pyrite and arsenopyrite, and low amounts of galena and sphalerite (Chye et al., 2001; and Ariffin & Hewson, 2007). Thirdly, gold associated with arsenopyrite and pyrite in quartz-carbonate veins and stringers (Chye et al., 2001; and Ariffin & Hewson, 2007).

Besides, gold commonly associated with sulfide minerals in quartz veins such as pyrite, arsenopyrite, galena, sphalerite, chalcopyrite, magnetite, pyrrhotite, and tetrahedrite-tennantite, and it also associated with antimony, especially stibnite (Sb_2S_3) and aurostibnite (Mandarino & Fleischer, 1995; Petruk, 2000; Millard, 2005; Makoundi et al., 2014; and Li et al., 2015).

Gold occurred in various grain size, and some gold particles were entrapped in very fine grained minerals (Petruk, 2000). In some quartz veins, gold was commonly found as coarse grain around 1 to 2mm, and small amount of gold occurred as disseminated particle range from 100 to 200µm infilling fracture of quartz-carbonate as well as sulfide minerals (Ariffin & Hewson, 2007; Alp et al., 2008; and Makoundi et al., 2014). In sulfide minerals, the gold mostly associated with pyrite in native form as inclusions in size range 1 to 50µm, also associated as sub-round inclusions in arsenopyrite and galena within the size range of 1 to 20µm. In addition, gold was also existed with pyrite along the boundaries of non-sulfide gangue. The average of invisible gold contents in pyrite and arsenopyrite varies from < 2.2 to 585 ppm, and in arsenopyrite from < 2.2 to 964 ppm (Kojonen & Johanson, 1999). Table 2.1 shows the summarize of gold-bearing minerals (Mandarino & Fleischer, 1995; and Petruk, 2000).

Table 2.1: Gold-bearing mineral (Mandarino & Fleischer, 1995; and Petruk, 2000)

Gold Alloys, etc		**Gold Alloys, etc**	
Native gold	Au	Sylvanite	$(Au,Ag)_2Te_4$
Electrum	(Au,Ag)	Kostovite	$CuAuTe_2$
Gold alloy	(Au,Ag,Hg)	Calaverite	$AuTe_2$
γ- gold amalgam	(Au,Ag)Hg	Montbrayite	$(Au,Sb)_2Te_3$
Weishanite	$(Au,Ag)_3Hg_2$	Krennerite	$(Au,Ag)\ Te_2$
Auricupride	Cu_3Au	Petzite	Ag_3AuTe_2
Tetra-auricupride	CuAu	Bilibinskite	$Au_3Cu_2PbTe_2$
Aurostibite	$AuSb_2$	Muthmannite	(Ag,Au)Te
Anyuiite	$Au(Pb,Sb)_2$	Bezsmertnovite	$(Au_4Cu(Te,Pb)$
Maldonite	Au_2Bi	Bogdanovite	$(Au,Te,Pb)_3(Cu,Fe)$
Zvyagintsevite	$(Pd,Pt,Au)_3(Pb,Sn)$	Buckhornite	$AuPb_2BiTe_2S_3$
Gold Sulfides		**Gold Selenides**	
Nagyagite	$Pb_5Au(Sb,Bi)Te_2S_6$	Fischesserite	Ag_3AuSe_2
Uytenbogaardtite	Ag_3AuS_2	Petrovskaite	AuAg(S,Se)
Criddleite	$TLAg_2Au_3Sb_{10}S_{10}$	Penzhinite	$(Ag,Cu)_4Au(S,Se)_4$
Buckhornite	$AuPb_2BiTe_2S_3$		
Secondary gold		**Invisible gold (Au as trace component)**	
		Mineral	**Gold component (range)**
Secondary gold		Arsenopyrite	<0.2-15,200 ppm
Auranitimonate	$AuSbO_3$	Pyrite	<0.2-132 ppm
		Leollingite	<0.2-275 ppm
		Terahedrite	<0.2-72 ppm
		Chalcopyrite	<0.2-7.7 ppm

2.4 Gold Classification

Gold ores can be categorized as refractory, complex and free milling ores depending on the mineral characteristics and mineral processing technique requirements (La Brooy et al., 1994). Refractory gold ore is complicated occurrence mainly in sulfide ore as fine-grained gold inclusion, and some parts are interlocking in sulfide minerals such as arsenian pyrite and arsenopyrite as nano-size of metallic gold, and stibnite (Chen et al., 2002; Vaughan, 2004; and Millard, 2005). This category does not provide economic gold recovery with conventional cyanidation (La Brooy et al., 1994; and Zhou et al., 2004). However, complex ore occurred in various geological environments, especially copper-gold deposit, and it gives acceptable economic gold recovery only with the use of significant reagents or more complex pre-treatment processes (Vaughan, 2004). Generally, free milling ore are found in placer gold deposits, quartz vein gold ore and oxidized ores in which the gold can be recovered by gravity or directed leaching. Moreover, free milling gold ore is completely liberated at 80% passing 75µm, and the gold recovery can achieve up to 90% (La Brooy et al., 1994; Zhou et al., 2004; and Vaughan, 2004).

The most significant of sulfidic refractory gold appears to be hosted by the pyrite, arsenopyrite and stibnite components of ore, which are amenable to flotation recovery. In some cases, gold is covered by pyrite, pyrrhotite and arsenopyrite (Badri & Zamankhan, 2013). In general, the recovery of refractory gold follows the same trend as the sulfide minerals (Teague et al., 1999). The major problem of sulfidic refractory gold ore is that very fine grain nature of some of the arsenical pyrite and arsenopyrite, mostly associated with silicate gangue minerals. Pre-concentrate of refractory sulfide gold ore is very important for further process, such as leaching or cyanide (Allan & Woodcock, 2001; and Marsden & House, 2006). The refractory gold ore can be processed by flotation or followed by roasting, bacterial leaching, or pressure leaching to liberate the gold before cyanidation (O'Connor & Dunne, 1994).

2.5 Physical and Chemical Properties of Gold

2.5.1 Physical Properties of Gold

Gold (Au) is a valuable, shiny, malleable and ductile metal, and it is good conductor of electricity and heat. Also, it is not affected by exposure to air or to most reagents (Kesler & Simon, 2015), and detailed gold's physical properties are demonstrated in Table 2.2 (Pellant & Pellant, 2014; Marsden & House, 2006; and King, 2017).

Table 2.2: Physical properties of gold (Pellant & Pellant, 2014; Marsden & House, 2006; and King, 2017)

Group	Native element
Crystal System	Face centered cubic (Isometric)
Habit	Crystals are very rare, cubes and octahedral, grain, nuggets, flakes, dendritic shapes
Cleavage	None
Fracture	Hackly
Color	Rich yellow
Streak	Golden-yellow
Luster	Metallic
Diaphaneity	Opaque
Cleavage	None
Mohs Hardness	2.5 to 3
Specific Gravity	19.3
Diagnostic Properties	Color, hardness, streak, specific gravity

2.5.2 Chemical Properties of Gold

Gold has the chemical composition Au, and insoluble in acids, except in aqua and selenic acid. It can be dissolve in water which is heated to 375 ^{o}C under high pressure (Kesler & Simon, 2015). It has an atomic number of 79 which is between platinum and mercury in Mendeleev's periodic table of the elements, and its atomic weight is 196.967 g/mol. It is a transition metal and belongs to a group 11 element which consists of copper, silver and gold. It has boiling point at 2808 ^{o}C while its melting point is at 1064.18 °C, and above this temperature it gives off a violet vapor (Pellant & Pellant, 2014). Details of chemical properties of gold is illustrated in Table 2.3 (Mindat.org, 2018, Marsden & House, 2006).

Table 2.3: Chemical properties of gold (Mindat.org, 2018, Marsden & House, 2006)

Properties	Value	Properties	Value
Atomic number	79	Atomic mass	196.9655 g/mol
Atomic radius	174pm	Electronegative radius	2.54
Ionic radius	137pm	Melting point	1064 °C
Ionic radius	0.137 nm (+1)	Isotopes	7

2.6 Usage and Production of Gold

2.6.1 Usages of Gold

Gold has been mined and used since the ancient time, it is valued due to its resistance to tarnishing, so it was used for special decorative ornaments. The majority of the gold produced is turned into gold bars nowadays (i.e., bullion that acts as the standard for the world's monetary systems), and they are used in international trade and exchange (Adams, 2016). 18% of gold is held by Central Banks, and the rest is in private stocks of bullion, coins, jewelry, or art objects, and electronic industries. More than 52% of world gold consumption was used as jewelry, 16% was held in investment funds, and 12% used in industrial applications ranging from catalytic converters to cell phones. Moreover, gold also used as a dental material, X-ray application, facial paralysis medication, and rheumatoid arthritis (Kesler & Simon, 2015).

2.6.2 Production of Gold

In the ancient time, the estimation of gold production for 7000 years is approximately 183,000 metric tons (Gosselin & Dubé, 2005). According to Mineral

Commodity Summaries (2016 and 2017), the countries, which are the most produce gold, are China (≈ 5%), Australia (≈ 9%), Russia (≈ 8%), United States (≈ 7%), and Canada (≈ 6%). China is the leading country as gold producer in 2015, 2016 and 2017 with the amount of 450, 455, and 440 tons, respectively. Australia is considered as the second country in the world as gold producer (Survey, 2017). The major gold production in the world are United States, Australia, Brazil, Canada, China, Ghana, Indonesia, Mexico, Peru, Russia, South Africa and Uzbekistan, and the amount of gold are shown in Figure 2.2.

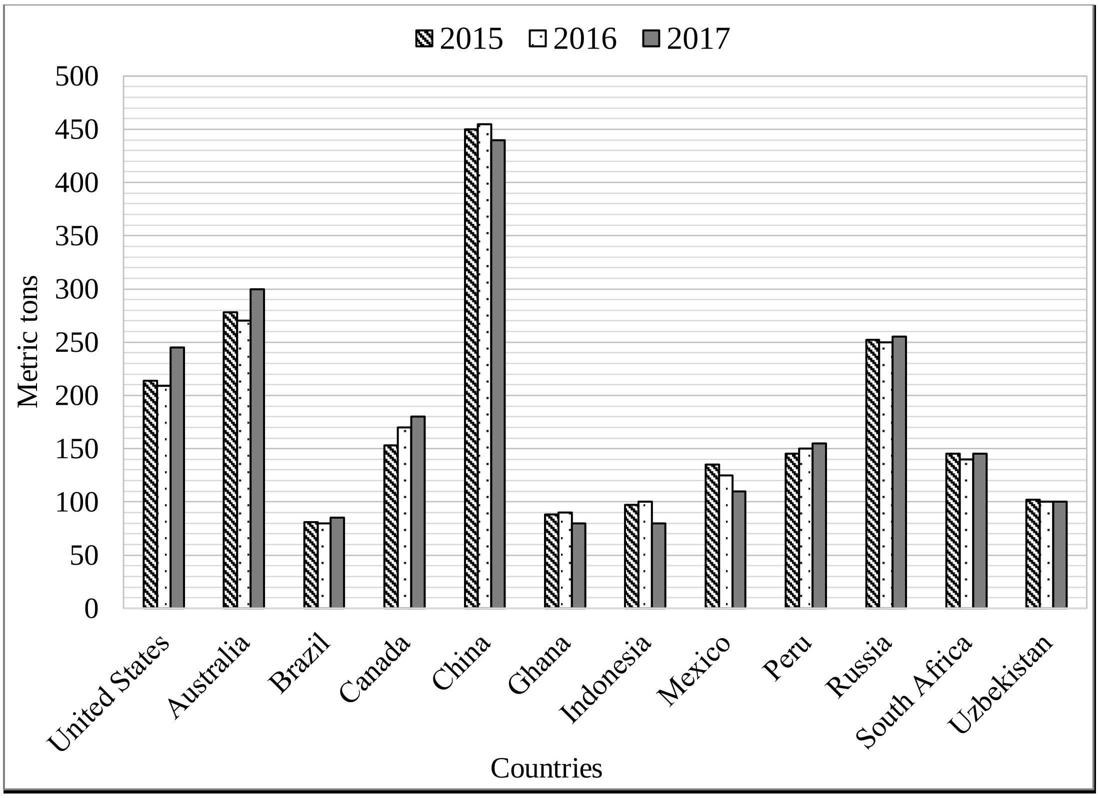

Figure 2.2: The countries of major gold producer in the world from 2015 to 2017 (Source: Mineral Commodity Summery, 2016 and 2017)

Malaysia is a country that is actively producing gold. In 2013, there are approximately 17 gold mines were operating in Malaysia which locates in the States of Kelantan, Pahang, and Terengganu (Pui-Kwan, 2013). Figure 2.3 reveals the gold production in Malaysia from 2006 to 2016. In 2006, Malaysia produced 3497 Kg of gold, and it kept decreasing to 2490 Kg in 2008 due to the low price of gold and lack of exploration, mine development and capacity in the local industry. However, it started increasing to 2794 Kg in 2009, and it was stable until 2010 before it straightly grew up to 4219 Kg in 2012 since Selinsing Gold Manager had increased the treatment capacity which higher amount of ore could be produced from 400,000 t/y to 1Mt/y (Monument Mining Ltd., 2013). In 2016, the gold production suddenly declined from 4723 Kg in 2016 to 2249 Kg about 52% in 2017 by the reason of lack of demand and low prices for most metals and minerals (USGS, 2017).

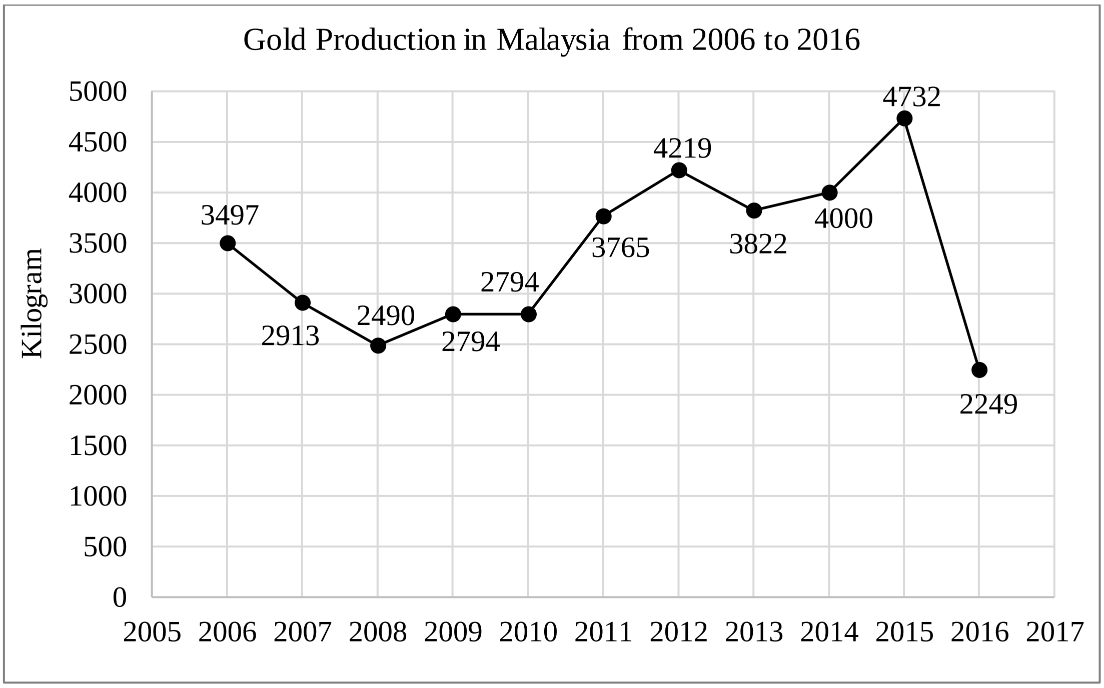

Figure 2.3: Gold production in Malaysia from 2006 to 2016 (Source: USGS Year Book 2009, 2013, 2014, and 2017)

2.7 Gold Mining Technology

Currently, the signification of gold for mining should be higher than 0.2g/t of gold grade (Marsden & House, 2006; and Pui-Kwan, 2013). There are various gold mining techniques which have been used with either placer (alluvial) or lode mines. For placer gold mine, gold can be recovered from alluvial sand and gravel, where hydraulic mining, gravel pump mining and gold dredge are normally carried out (Butterman & Amey III, 2005; and Min, 2006). However, lode gold mine refers to vein gold mining, and commonly veins change direction frequently, and it can be achieved by dry mining, such as surface and undergroud mining. Gold mining technique depends on the geometry of ore body which be achieved by either surface or underground mining, or both methods in some cases (Hartman & Mutmansky, 2002; and Vieira, 2006). Additionally, hard rock mining can be achieved by open pit or open case, dry mining, or underground mining (Mudd, 2007).

Open pits are applied to acheive shallow deposits (near the earth surface) that has a low stripping ratio, which can provided high productivity and acceptable safety condition. But it needs a large capity, and in surface mining, it is neccesary to take off the top layer (soil and rock) or overbuden to reach ore body by dry mining including drilling, blasting, excavation, haulage and hoisting (Hartman & Mutmansky, 2002). For instance, in Australia, most of the mine has operated with open pit, and it provided 75% of Austria's gold production (La Brooy et al., 1994). Similarly, there are several open pit gold mines in Malaysia such as Pejom gold mine, and Selinsing gold mine, where the excavators were used to dig the gold bearing ore onto dump trucks to transfer to the connected area in front of palong (Min, 2006). Nevertheless, underground mining technique is also used when surface mining cannot be achieved. For the deep gold deposits, underground mining technique is applied to excavate the ores beneath the earth's surface through tunnels or shafts. The ventilation system is required for workers safety (Hartman & Mutmansky, 2002). Underground mining had been carried through gold mining, Central belt in the ancient time (Miller, 2014). As revealed by Akcil (2002), open pit (could produce 200,000 ton/year) and underground mining (could produce 100,000 ton/year) were employed together at Ovacik gold mine, Turkey.

The gold extraction from alluvial, colluvial or elluvial is mostly carried out by hydraulic mining, dredging, gravel pump mining which were effective for gold mining around the world as well as in Malaysia, especially for alluvial mining in Perak and Selangor. Hydraulic mining is a combination of dredging and conventional mining, and the rock is disaggregated and washed by a jet of water into a processing facility (Butterman &Amey III, 2005; Vieira, 2006; Min, 2006; and Kesler & Simon, 2015). The principle of the monitor in hydraulic mining is uses the high-pressure jets of water (hydraulic monitor) to dislodge rock materials of placer deposits for mineral removing by the corrosive action water. The rocks and sediments then move down directly through the sluice box (palong) or to the seam in order to extract gold (Hartman & Mutmansky, 2002; and Harraz, 2010). Similarly, Dredging is one part of hydraulic mining, which is used to remove gold ore from underwater, such as sand, gravel and soil by using water mechanically or hydraulically. The extraction of gold is carried out by floating vessels (Hartman & Mutmansky, 2002).

Additionally, gravel pump is a revolution of hydraulic mining as the hydraulic elevator was replaced by the hight efficiency gravel pump to transfer the ground sluice to the sump in gold mining by the water jets from the monitors. The slurry is then washed to a sump in the pit floor before going through palong for gravity separation (Min, 2006; and Vieira, 2006). The gravel pump's capacity operation depends on the gravel pump's suction intake (ranges from 7 to 25 cm), which can operate between 45 and 15 m^3 weekly base on type of materials and possibility of equipment. Meanwhile, it needs to be properly cleaned after 2 to 10 operating days to remove the blocking aggregates (Vieira, 2006).

2.8 Gold Processing

Processing of gold is very crucial in order to extract the gold from gangue minerals. There are various methods either physical or chemical techniques to extract gold from ore such as gravity concentration (shaking table, Mozley table, palong, gold pan, etc.), high tension separation, froth flotation, amalgamation, heap leaching, cyanidation, etc. (Napier-Munn & Wills, 2006; and Adams, 2016). In some cases the recovery of gold by gravity concentrators by using panning, sluice box, shaking tables, spirals, froth flotation, Knelson and Falcon were used to preconcentrate the ore prior to accomplishing with chemical processes (Lunt & Weeks, 2016; and Deschenes, 2005).

2.8.1 Gravity Concentration

Processing of gold by gravity method refers to the separation of gold from gangue minerals by differences of mineral's densities. This separation is more effective when the narrow particle size range of minerals are operated, and it is commonly operated with placer gold (Vieira, 2006; and Wills & Finch, 2015). Sluice box (palong), panning, shaking table, etc. are the most popular methods which are usually used in gold processing plants (Maponga & Ngorima, 2003; Sayontan, 2011;Wills & Finch, 2015; and Angove & Acar, 2016).

Generally, gold extraction processes can be achieved by a combination of unit operations. For example, in small scale gold surface mining at Licuan Baay in Philippines, the gold processing plant was conducted by sluice box (palong) as a primary concentrator, and panning was ultilized as the final step to concentrate the sluice's product as shown in Figure 2.4 (Bernaldez & Soriano, 2017).

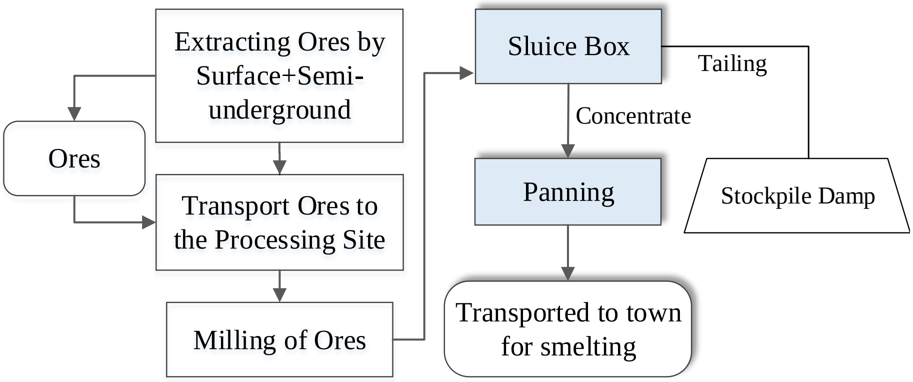

Figure 2.4: Typical flowchart of the gold processing in Licuan Baay(Bernaldez & Soriano, 2017)

(a) Sluice Box/ Palong

Palong is the most important structure in mining, and the efficiency of gold recovery would depend on its design. It is a big wooden sluice box which has single or twin lanes or more. Typically, the dimensions of slice box are 50m long and 2m wide lane, and the size of riffle for trapping ore is 100mm x50mm (Min, 2006). The concentration ratio could be upgraded very high using sluice box, approximately in the range of 10,000:1 to 500,000:1 (Vieira, 2006). Typical gold palong in Malaysia is displayed in Figure 2.5 (Min, 2006). Gold recoveries could be accomplished up to 80% by using sluice box, yet the lower recovery due to fine gold lower than 200 µm and flaky in shape of particle might be the reason that gold went to the tailing (Mitchell et al., 1997).

Figure 2.5: Palong for gold mining in Malaysia (Min, 2006)

(b) Panning

Panning is the oldest technique used to recover gold from river bank and some alluvial deposits. The procedure of gold panning is the materials from alluvial deposits or crush ore were scooped into the pan where then gently agitated in water is applied (Figure 2.6 (A)). The gold and higher specific gravity of materials sink to the bottom of the pan, as shown in Figure 2.6 (B), while the lighter materials spill out of the pan (Gasparrini, 1983). The construction of god pan was found either made of wood, metal or plastic with variety of design and size. The standard of American gold pan ranges between 15 to 18 inches in diameter at the top and 2 to 2.5 inches in depth. The side sloping is typically 30 to 45 degrees. Recently, 14 inches (36cm) diameter size has been commonly used, and in Malaysia, pan normally made of wood, plastic or metal (Silva, 1986).

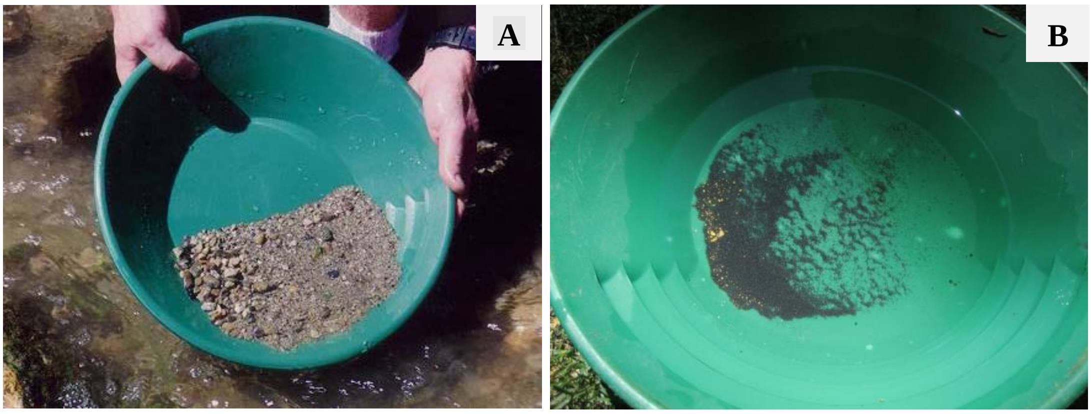

Figure 2.6: (A) Panning procedure, and (B) gold contained in the bottle of panning (Silva, 1986)

(c) Shaking Table

Shaking tables are considered as the environmentally friendly method in mineral processing as only water is used. In this operation, the feed size is in the range of 3mm to 100µm for coarse grain size, called sand tables. Nevertheless, for the particle finer than 100µm, the table were designed as slime tables which the decks have a series of planes instead of riffles to trap the gold or other heavy metals (Wills & Finch, 2015; and Mitchell et al., 1997). Both alluvial ores and crushed bed rock ores are possible to be concentrated by shaking table, and the recovery was achieve up to 90%. Mitchell et al. (1997) and Tahli & Wahyudi (2013) found that the most efficient of gold separation process was the size range 3mm to about 50µm.

2.8.2 Chemical Mineral Processing of Gold

There are several common chemical processing methods such as cyanide leaching, mercury amalgamation and bioleaching of refractory gold ores, were accomplished for gold recovery (Lunt & Weeks, 2016; and Deschenes, 2005).

(a) Cyanide

Cyanide leaching is also considered to treat the complex ores by intervening of preg-robbing and oxygen consuming, and cyanide with carbon in-pulp/carbon-in-leach recovery usually works with free milling ores (La Brooy et al., 1994). Cyanide has been widely used to recover gold from gold bearing ores since the 1890s. It is one of the most popular method which is usually used in heap leaching process. It also replaced the toxic mercury amalgamation method. Gold oxides may passivate the reaction in less acidic solutions, and this is readily overcome by leaching in acidic solutions (Adams, 2016).

The mechanism of gold cyanide leaching can be simplified by Equation 2.1 where gold is dissolved in cyanide solution. The dilute solutions of sodium cyanide in range of 100 to 500 ppm are used in tank leaching in the presence of lime and oxygen, and the reaction was followed by Equation 2.2 (Logsdon et al., 1999; Deschenes, 2005; and Marsden & House, 2006).