

## Mill leaching: a viable substitute for mercury amalgamation in the artisanal gold mining sector?

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### ABSTRACT

Artisanal small-scale gold miners (ASM) occasionally employ whole ore amalgamation by adding mercury into ball mills to recover gold. In this process, 25–30% of the mercury added is lost to the environment. It is also inefficient less than 30% of gold is recovered. Amalgamation, followed by cyanidation, has been observed at many artisanal mining sites. This combination poses additional environmental and health consequences. Tests with ore samples from Talawaan, North Sulawesi, Indonesia indicate the possibility of replacing mercury by cyanidation in the ball mill, reaching gold extraction of 93% in 6 h of leaching. The gold in the Indonesian ore sample is fine and less than 8% of gold recovery was obtained with gravity concentration of the ore ground 80% below 0.25 mm, which is a reasonably fine grain size for artisanal gold operations. Replacing mercury addition with cyanidation in ball mills was implemented in one artisanal gold mining operation in Portovelo, Ecuador, achieving 95% of gold extraction in 8 h of mill leaching. This technique demonstrated a drastic improvement in gold recovery. It was found to be a simple, inexpensive technique well accepted by local miners. The results from laboratory and field tests are promising; however a thorough investigation into the socio-economic and environmental aspects of this presented alternative must be conducted prior to introduction.

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### 1. Introduction

Due to its efficiency, gold amalgamation is a common practice in the artisanal and small-scale mining (ASM) sector. At the same time, however, it generates significant mercury (Hg) emissions, resulting in a host of health-related and environmental problems. ASM practices release approximately 1000 tonnes of Hg annually to the environment. There are 10–15 million artisanal miners [1] in more than 70 countries [2] working directly with gold, and due to lack of knowledge and alternatives, thousands of miners and community members have been poisoned by Hg [3]. It is estimated that 30% of Hg used by ASM is lost to the atmosphere when miners roast amalgams in open air. Approximately 70% of Hg is lost when the whole ore is amalgamated; either through the utilization of copper-amalgamation plates or through the addition of Hg directly into ball mills [1].

When Hg is used inside ball mills to amalgamate the whole ore, as observed in Indonesia, Ecuador and Colombia, the amount of Hg lost is at least 10 times the amount of gold produced. It has also

been observed in various field trips to these countries that the amalgamation of the whole ore in ball mills is a very ineffective process and gold recoveries are usually not higher than 30%. When only a small portion of concentrate from sluice boxes or centrifuges is amalgamated, the  $Hg_{\text{lost}}:Au_{\text{produced}}$  ratio is around 1 and can be even lower if retorts are used to recycle the evaporated Hg during the roasting process [4]. The amount of gold recovered by amalgamation of concentrates is not always higher than when the whole ore is amalgamated since recovery is governed by gold grain liberation, i.e. by the efficiency of the grinding process. However, Hg loss is substantially higher when amalgamation is conducted in ball mills. Tailings from whole ore amalgamation usually contain 50–200 mg of Hg/kg of ore and are often discharged into water streams. Discharged Hg can then be oxidized and complexed; these are the preliminary steps in the transformation of metallic Hg into a more toxic form, methylmercury [5]. In addition to developing environmental awareness programs, it is crucial to work towards the elimination of practices such as the amalgamation of the whole ore and evaporation of Hg from amalgams in open air.

The replacement of mercury amalgamation with any other process seems to be a site-specific issue. Replacement is dependant on investment capacity, level of education and motivation of miners. Support of local authorities to promote and sustain technological alternatives is critical. To date, no panacea or methodology

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that can be widely promoted exists. Each case must be studied carefully and a thorough evaluation of the socio-economic context must be conducted before suggesting any alternative process. With this in mind, the objective of this study was to evaluate the technical feasibility and environmental advantages of introducing an alternative process, such as cyanidation in ball mills (herein referred as “mill-leaching”) replacing completely the use of Hg.

The first part of this study was conducted in the laboratory using ore samples from Talawaan, North Sulawesi, Indonesia. Unfortunately, field implementation in Indonesia was not feasible, as the Indonesian Government introduced legislation restricting the use of cyanide in artisanal gold mining operations (however, miners continue to gain access to and use cyanide in their operations, as they have for over a decade). The administrative procedure for the use of cyanide in North Sulawesi for research purposes would be far too complex and slow. As an alternative, field tests were conducted in Portovelo–Zaruma, Ecuador. As Ecuadorian artisanal miners perform whole ore amalgamation in ball mills, the results of this investigation are easily applicable to other sites with similar characteristics, such as Talawaan, Indonesia or Northeast Antioquia, Colombia. This study was part of the Global Mercury Project, a project sponsored by the Global Environmental Facility (GEF), United Nations Development Programme (UNDP) and implemented by the United Nations Industrial Development Organization (UNIDO).

## 2. Gold processing techniques and ASM

Since the invention of gold cyanidation in the late 1800s, this process has replaced amalgamation for industrial operations as it is more efficient at extracting fine gold. In addition, most cyanide compounds decompose in the environment into less or non-toxic forms (nitrogen and carbon dioxide). Conversely, Hg remains in the environment in its metallic form or eventually forms more toxic and persistent soluble compounds.

In ASM operations, the capital and operating costs required to process gold ores either by amalgamation or cyanidation are usually higher than the manual ore extraction costs, except when the processing is conducted in a very rudimentary way, such as manual panning, as observed in some parts of Africa [6,7] and Asia [8]. Just a few artisanal miners can afford to have their own processing plants. This has created a number of “custom” or “toll” milling centers which are Processing Centers in which miners pay to crush, grind, concentrate and extract the gold from their ores. This practice has been observed by the authors in field trips to countries such as Brazil, Chile, Colombia, Indonesia, Ecuador, Tanzania, Venezuela and Zimbabwe. In Zimbabwe for example, there were as many as 243 Processing Centers operating as of September 2007 [9]. The proliferation of this procedure was quickly noticed since, worldwide, the Processing Center’s owners adopted the cheapest and less efficient process to recover gold for their clients: amalgamation. Gold processing is typically offered to miners for free or a token fee, if miners agree to leave tailings at the Centers. These Centers rarely recover more than 30% of the gold brought by the miners. The residual gold left in the Centers is then extracted by cyanidation from the mercury contaminated tailings. A key issue in this scenario, is that cyanide dissolves not only gold but also any remaining Hg left behind from the amalgamation process, forming mercury cyanide, which is either more bioavailable or easier to be methylated than metallic Hg when discharged into the water streams. The environmental impacts of mercury cyanide released by ASM can be followed by high levels of Hg in fish in regions where amalgamation and cyanidation have been used simultaneously [10–12].

There are several alternatives to replace Hg amalgamation with other reagents such as thiosulphate, thiourea, bromine, chlorine, etc., although most are not suitable or affordable to artisanal miners [13–17]. Importantly, technology is only one of the three barriers discussed by Hilson [18] to implement cleaner mining practices. The legislative and economic barriers can be very complicated in the artisanal gold mining sector as most governments are not prepared to understand the benefits and idiosyncrasies of this poverty driven activity. Any change on labor procedures used by the artisanal miners will not be possible if governments do not engage mining communities in dialogue in a transparent way, considering their needs and expectations. In contrast, the field-intervention approach is rewarding as results of technological changes are visible and measurable. Unfortunately, the implemented measures are rarely sustainable if a permanent technical assistance is not established [19]. Hilson [20] discussed several cases of interventions in ASM sites to reduce Hg emissions and observed the lack of sustainability of these endeavors, in many cases due to lack of institutional support. Education at all levels seems to be the most sustainable procedure to introduce cleaner procedures into ASM sites [21].

Cyanide is definitely the most promising reagent to replace mercury. Almost the totality of mining companies uses sodium or potassium cyanide to leach gold. The process works very well and exposed grains of gold finer than 0.2 mm can be leached in 24 h in low concentrations of cyanide (50–1000 mg/L of cyanide), in alkaline solutions (pH10–11), under aeration:  $4\text{Au} + 8\text{CN}^- + \text{O}_2 + 2\text{H}_2\text{O} = 4\text{Au}(\text{CN})_2^- + 4\text{OH}^-$ . Once gold is in solution, it can be precipitated with zinc ( $2\text{Au}(\text{CN})_2^- + \text{Zn} = \text{Zn}(\text{CN})_4^{2-} + 2\text{Au}$ ) or adsorbed on activated carbon (usually 5–10 kg Au/tonnes of carbon). The advantage of the carbon process is no filtration is needed since carbon is mixed with the ore pulp (around 30% solids), screened, washed and the gold is desorbed with a caustic solution with or without cyanide and ethanol. The zinc precipitation process (known as Merrill–Crowe Process) is simpler but, the solution must be clear (e.g. settled or filtrated) and, for efficient precipitation, air must be removed. The zinc process has been used by many artisanal miners in Ecuador and Colombia and is useful when the gold grade of the gravity concentrate being leached is high, otherwise this could saturate the activated carbon resulting in gold loss to the solution.

Any technical solution to be successfully implemented in ASM regions must be simple, fast, inexpensive, and more efficient than amalgamation. Worthwhile attempts to introduce efficient and affordable processes to replace amalgamation have not resulted in any significant breakthrough. This is the case of the iGoli process developed by MINTEK in South Africa [22,23], a process to dissolve gold from gravity concentrates with hypochlorite in acidic medium followed by precipitation with sodium metabisulphate. Despite the efforts of the South African Institute in demonstrating the high gold recovery levels of this process over amalgamation, there is a long educational process to convince miners that this alternative process is better than any traditional one. All other methods using gravity concentration to completely replace amalgamation have not succeeded for all cases, since this depends on the mineralogical characteristics of the ore. The most recent developments, the iCon–Falcon centrifuge (iCon–Falcon Concentrators, <http://www.iconcentrator.com>) and the magnetic sluice box promoted by Cleangold® [24] are great advances on recovering more gold by gravity concentration, but the recovery efficiency depends on the characteristics of the gold ore such as shape of the gold grains, type of deposit, gold grain size, liberation, and type of associated minerals. The iCon is a low weight (100 kg) centrifuge manufactured by Falcon Concentrators that can process up to 2 tonnes of ore/h. This centrifuge was designed for artisanal miners and operates with variable speed (up to 150 G). Most parts of the machine

can be easily fabricated locally and the price of the whole centrifuge is below US\$ 5000 (FOB Vancouver, Canada). The company has to date sold approximately 200 of these machines worldwide. The iCon has been successfully tested in Brazil (Tapajos Region) and the concentrate is leached with cyanide using the mill-leaching process herein described. The Cleangold (Cleangold. Mercury-free gold mining, <http://www.cleangold.com>) is a small magnetic sluice box that attracts magnetite (when this mineral is present) or shavings and bits from the grinding media (e.g. hammer mill), forming a sort of magnetic “carpet” on the sluice surface that concentrates fine gold [25].

If the grade of the gravity concentrate is high, a large amount of gold can be recovered without Hg by panning. However, some gold is left behind in this process. By using cyanide, hypochlorite or any another reagent to extract fine gold particles, typically more than 95% of the gold can be extracted if the process is operated properly. Even amalgamation of concentrates can be efficient but this depends on two factors: 1) gold must be liberated from other heavy minerals, and 2) Hg must be “clean” (activated). For example, amalgamation of a gravity concentrate can be very inefficient (<70% gold recovery) if the Hg is “dirty”, i.e. “oxidized”. Pantoja and Alvarez [26] developed a process to activate Hg, forming a sodium-amalgam, using a 12-V battery. This process increases substantially the amount of gold recovered from concentrates and reduces Hg losses. In Brazil, this process had a tremendous impact as 92% of the 4200 miners trained by the Global Mercury Project introduced this technique to their daily process [12]. In fact the use of any gravity concentration process reduces substantially the mass of the material to be amalgamated and thus reduces Hg losses to the environment compared to when the whole ore is amalgamated.

Main efforts of Governments have been towards formalization of artisanal mining instead of providing technical assistance to reduce mercury emissions and occupational exposure to mercury vapor. Any formalization must bring economic benefits to miners and should also be implemented in harmony with the neighboring countries, otherwise miners will find a way to smuggle gold to other countries [27]. A mining title is definitely an important step to provide miners with a transferable property, but knowledge is more important in order to engage them into a transition from artisanal-rudimentary-polluting activities to small-scale-mercury-free mining operations [28].

### 3. ASM in North Sulawesi, Indonesia

Artisanal gold mining is an old activity in Indonesia, and relies mainly on manual labor using very rudimentary methods. According to Limbong et al. [29] approximately 10,000 miners are actively working in artisanal gold mining and processing in the North Sulawesi Province of Indonesia (Fig. 1). The Talawaan watershed area (34,400 ha), also known as Tatu region, has a population of 150,000 mostly devoted to rice, coconut, clove and nutmeg plantations as well as fish farming. These were the main economic activities prior to 1998 when the Australian company, Aurora Mining Co. of Australia (nowadays Archipelago Resources Pty Ltd.), found gold Northeast of Manado City and the miners invaded their exploration concession. Estimates suggest 10,000 illegal miners are working in the region.

The ore is manually mined from narrow shafts, 20–30 m deep. The ore is placed in bags and transported to the Processing Centers. Miners extract between 0.5 and 1 tonne/day of partially weathered ore with average gold (Au) grade ranging from 5 g to 10 g Au/tonne. The material is crushed to  $-1/2$  inch using dry stamp mills. Processing units have from 12 to 48 homemade steel ball mills (known locally as *tromels*) with diameter of 48 cm and length of 60 cm. One mill grinds 40 kg of ore for 4 h using 40 river pebbles (5–10 cm) or steel balls. The grinding step is then interrupted and 0.5–1 kg of mercury is added per mill. The mill runs for an additional hour. Each mill processes 400 kg of ore before the gold amalgam is removed. The ground product is mostly finer than 150 mesh (0.105 mm). This procedure loses one third of the mercury added into the ball mill. Hg and the amalgam are separated by panning in a plastic tub and manual filtration using a piece of canvas. The resulting amalgam is decomposed by heat either using a retort with water cooling system or simply roasting in open air. Very few miners use retorts despite the efforts of the German Institution, GTZ, to promote a stainless steel retort to recycle Hg [30], either due to the high price of the equipment or because miners are not sensitized to adopt safety procedures to avoid Hg exposure and emissions [31].

A processing unit with 12 mills recovers 4–6 g of gold per cycle (0.3–0.5 g Au/mill). Typically there are two cycles operated per day. The mills operate 8 h/day, 6 days a week. Martens [32] estimated that in July 2000, 200–250 milling units were operating in the Talawaan (Tatelu) region. Limbong et al. [29] estimated that, in June

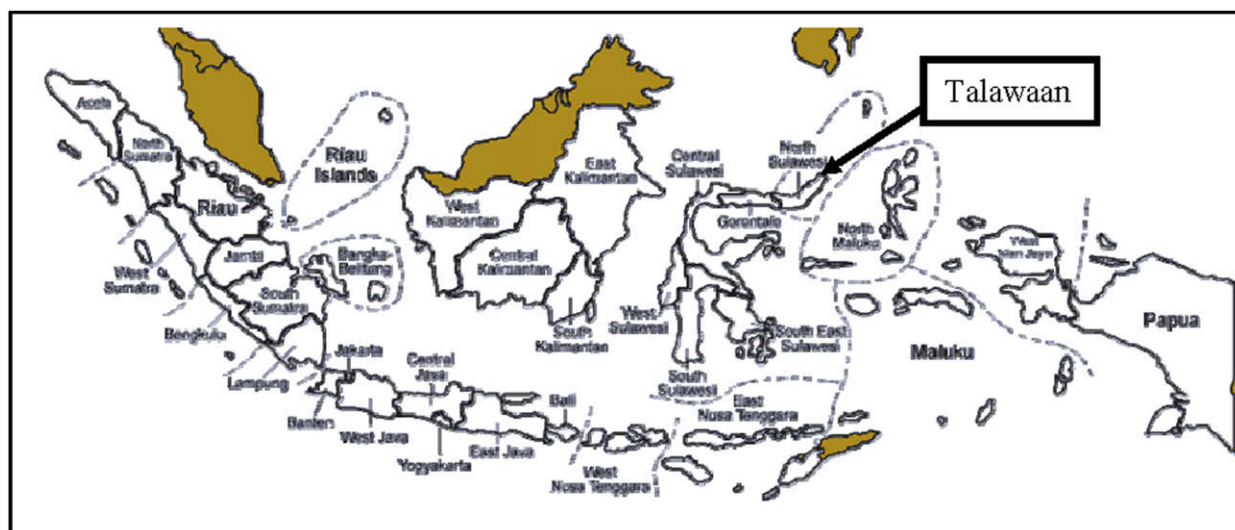


Fig. 1. Site location in Indonesia where samples were collected for laboratory tests (Source:[www.indonesiamatters.com/images/indonesia-map.gif](http://www.indonesiamatters.com/images/indonesia-map.gif)).

2001, there were 400 gold processing plants using amalgamation in North Sulawesi region. The author visited 133 milling operations in the Talawaan watershed (Tatelu region) and found that mill operators have purchased from 10 to 30 kg/month (average of 15 kg/milling unit) of Hg. Hg loss in the region was estimated to be between 24 and 90 tonnes per annum.

Miners store the amalgamation tailings in rice sacks to be sold to the cyanidation plants. In North Sulawesi there are at least 200 cyanidation tanks. The owner of a leaching unit pays the equivalent of US\$ 0.40 per bag of 40 kg of amalgamation tailings. One cyanidation tank leaches 20 tonnes of material per batch using 100–200 mg/L NaCN at pH 11 adjusted with lime and controlled once a day. A small tank that pre-agitates the pulp with 30% solids recovers some Hg that settles at the bottom of the tank (300–500 g Hg recovered per 20 tonne batch). Operators claim that the totality of residual Hg is recovered in this process, but they do not have analyses of the material before and after the settling tank. A simple air compressor carries out the aeration of the pulp which is not effective. For this reason, the leaching process lasts 2 days. Between 100 and 150 kg of activated carbon is then added to leaching tanks. After 3 batches, or approximately 60 tonnes of material processed, the carbon is recovered by screening and re-used, and tailings are deposited in a large non-lined tailing pond. Miners indicated that occasionally sodium hypochlorite is added to destroy residual cyanide, however natural cyanide degradation is relied upon. As operators lack knowledge about the elution processes to extract gold from activated carbon, the Au-loaded carbon is burned in open drums to recover about 400 g of gold per load of 20 tonnes of tailing. Very often miners amalgamate the ashes of the burned carbon. The leaching plant owners pay US\$ 1.4 for 1 kg of activated

carbon. It is estimated that 50% of miners utilizes amalgamation before selling ore to the cyanidation plants whereas others conduct cyanidation of the whole ore.

Mercury amalgamation has caused many environmental and health impacts. According to Limbong et al. [29], Hg is often discharged into inadequate tailings ponds, or is disposed directly into rivers. Castilhos et al. [10] also mention that this process generates amalgamation wastes highly contaminated with finely dispersed Hg droplets. Miners also use cyanide to recover residual gold from these contaminated wastes, and this process increases the bioavailability of Hg in aquatic systems. Gunson and Veiga [33] investigated the effects of leaching Hg-contaminated tailings in China through cyanidation and observed that cyanidation tailings present less Hg than the original amalgamation tailings, while a large portion of the Hg is water-soluble and much more bioavailable than metallic mercury.

#### 4. ASM in Portovelo–Zaruma, Ecuador

For more than one hundred years gold mining has been the main economic activity in the region of the towns of Zaruma and Portovelo located in the Province of El Oro (Fig. 2). The current high gold price and the agricultural crisis, caused by the El Niño phenomenon [34], have led to the intensification of the informal mining activities in Ecuador. The vast majority (85%) of the gold production in the country comes from the artisanal small-scale mining sector, and approximately 70% of gold produced is sold to the black market. The main mining sites are Zaruma, Portovelo, Ponce Enriquez, Bella Rica, Nambija and Guayzimi Districts. The number of artisanal gold miners in Ecuador can be as high as



Fig. 2. Location of Zaruma–Portovelo mining district (Source: <http://www.exoticbirding.com/images/ecuador-map.gif>).

100,000, and the annual mercury emission from these operations is estimated to be very high. A survey accomplished by the Swedish Environmental System estimated discharges of mercury 40 kg per year in the River Siete and 160 kg per year in the River Calera [35].

In the Zaruma–Portovelo region there are 104 Processing Centers using amalgamation and cyanidation and approximately 10,000 people directly involved in mining and processing activities. In these processing plants, about 9 tonnes of gold is produced annually in the region. The underground ore is mined manually mostly in the mountainous region of Zaruma and miners take 1000–2000 bags of ore (each bag with 40–50 kg) with grades ranging from 3 to 30 g Au/tonne of gold to be processed at the Centers in Portovelo. The Centers' employees grind the ore, concentrate gold in sluice boxes and amalgamate the ore for free or for a low fee. In return, the miners give the tailings to the millers to extract residual gold by cyanidation using CIP (Carbon-in-Pulp) process.

Processing involves the grinding of wet ore in Chilean mills operating in the Processing Centers producing material with grain size below 0.2 mm classified with a nylon screen at the mill discharge. A Chilean mill typically grinds and concentrates 200 bags or 10–12 tonnes per day. The ground material is discharged on 7–10 m long cement sluice boxes covered with locally made wool carpets. Miners remove 5 bags or 250 kg/day of concentrate (or 2.5–3% of the ore mass) from the carpets, usually with a grade ranging from 10 to 30 g Au/tonne. This is in fact a pre-concentrate; the low gold grade of the concentrate results from frequent cleaning of the material retained in the carpets then preventing the gold from accumulating. As the gold is fine, the miners prefer to improve the gold recovery by frequent carpet cleaning, sacrificing the grade. After five days of grinding, miners wash the Chilean mill to recover the gold left inside the mill by amalgamation of the whole material.

A large amount of concentrate is panned in a water box and then amalgamated in a steel pan locally known as “*platon*”. In this process, the millers add 100 g of mercury and 700 g of brown sugar to amalgamate gold from 3 kg of concentrate. The ratio Hg:concentrate is actually low (1:30) compared to artisanal mining operations in other Latin American countries such as Venezuela and Brazil [36,4]. Amalgamation is conducted manually forcing the Au–Hg contact with a large polished stone. The pH of the concentrate pulp does not change with the introduction of sugar and remains constantly 6 during amalgamation. The amalgamation process lasts 50–90 min per 3 kg of concentrate.

Some miners, use a large steel amalgamation barrel, known as a “*chancha*” (diameter of 0.8 m × length of 1.5 m) to proceed the amalgamation of the material left inside the mill or high grade ores. This is similar to a small ball mill but using either round stones or steel rods. Miners add 150–200 kg of material into these barrels together with 454 g (1 lb) of mercury and 1.5 kg of brown sugar (apparently to reduce the surface tension of mercury). The “*chanchas*” rotate for 3.5 h and miners recover typically less than 70% of the mercury added. Mercury is pulverized and lost with fine particles. The amalgam typically contains around 50–60% of mercury. Retorts to burn amalgams are not widely disseminated in the region [37] and from 1 to 2 parts of mercury are lost to the environment for each part of gold produced when the amalgam is burned in rudimentary fume hoods (some of them have exhaustors and water scrubbers). The whole amalgamation process recovers as much as 30–50% of the gold from the ore, depending on the mineralogy of the material. Remaining gold is left in the plant to be leached with cyanide (CIP Process).

Gravity concentration tailings, usually with grades between 2 and 5 g Au/tonne, typically 3 g Au/tonne, are stacked and de-watered to be transported to the cyanidation tanks owned by the Processing Centers. The agitation of 15–17 tonnes of tailings is done

mechanically or with compressed air using concentrations of cyanide between 1000 and 5000 g/L which is 10–20 times higher than concentrations used by industrial companies [38]. The consumption of NaCN in the region ranges from 1.5 to 3 kg NaCN per tonne of tailing depending on the amount of copper minerals in the material. The residence time of the cyanidation ranges from 10 to 72 h, typically 24 h. The pH is kept around 10.5 in the CIP plants.

Recently, miners were observed using the Merrill–Crowe Process (cyanation followed by gold precipitation by zinc) to leach the pre-concentrates from sluice boxes (Fig. 3). These are rudimentary concrete tanks of 10–15 m<sup>3</sup>. Most miners operate at pH 10–11, but they have no control of the pH. In few plants it was observed cyanidation at neutral pH. Some millers do not understand the danger of working with cyanide at pH 7 or 8 and are exposed to high concentrations of cyanide gas. While cyanide cannot be bioaccumulated, its decomposition (oxidation) produces cyanate and thiocyanate that can be bioaccumulated resulting in thyroid toxicity, including goiter and cretinism [39–41]. A high incidence of goiter in Portovelo and stomach cancer was reported by a local doctor in Portovelo, however no systematic data was available. Employees at a Processing Center leaching gold at neutral pH were asked why they do not operate the cyanidation tanks at higher pH, they answered “*without the cyanide smell we do not believe that the gold is being leached*”. At low pH, toxic HCN gas is formed which is lost to the atmosphere when miners become exposed.

The zinc precipitation process is a way to obtain gold faster than using activated carbon. The whole process usually takes 5 days and consists of 12 h of mechanical agitation, settling of solids in the tank, and re-circulation of the clear solution through the zinc and back to the tank for 4.5 days. Lack of a filtration process results in losses of 5–10% of the total leached gold retained as solution in the settled material. Zinc precipitation occurs in four Ø15 × 50 cm PVC pipes filled with zinc shavings. The process is not conducted in vacuum. The precipitated gold is recovered by burning the zinc in open air, a process that also volatilizes any mercury that has co-precipitated with gold.

The Processing Centers' owners are responsible for waste management. Except for some well-structured plants, waste

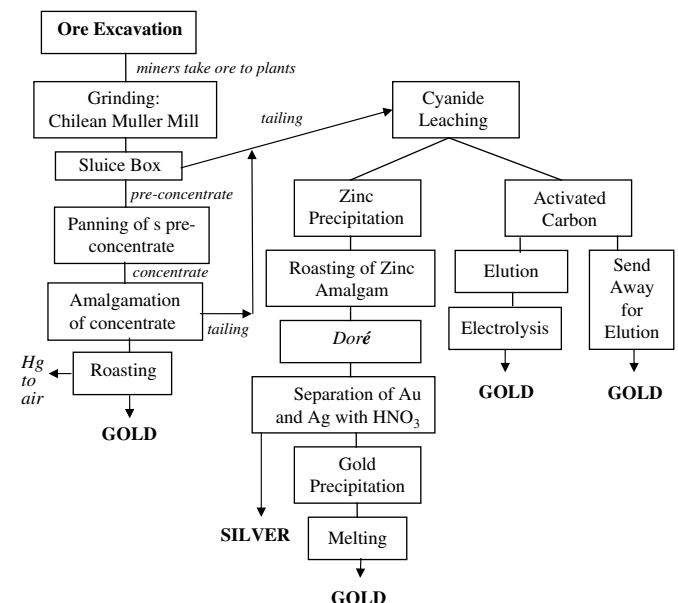


Fig. 3. Gold processing scheme used by ASM in Zaruma–Portovelo, Ecuador.

management in the area is very poor and in many cases non-existent. Cyanide is not destroyed and tailings containing residual mercury and cyanide are not totally removed from the pulp by activated carbon or precipitated by zinc and thus are subsequently disposed in the Amarillo River.

## 5. Laboratory tests with ore sample from Indonesia

### 5.1. Methodology

A series of tests were conducted to assess the mercury-free processing possibilities for a specific gold ore collected in Kotamobagu, North Sulawesi. The tests were designed to assess the gravity recoverable gold, to compare gravity concentration versus cyanide leaching and to study the kinetics of gold dissolution by grinding in presence of cyanide ("mill-leaching"). Solids were analyzed by fire assay followed by Inductively Coupled Plasma Emission Spectrometry (ICP-ES) and solutions were analyzed by Instrumental Plasma Mass Spectrometry (ICP-MS) at International Plasma Ltd, Vancouver, Canada.

For gravity concentration, a lab scale Knelson centrifugal concentrator was used and the test followed Laplante and Spiller procedure [42]. An 82 kg ore sample with 6.02 g Au/tonne was crushed below ¼ inch (80% finer than 5 mm) in jaw and cone crusher. The crushed ore was homogenized and split to obtain representative portions for testing. The test consisted of four sequential steps involving gravity concentration followed by regrinding of the tailings prior to the next stage of gravity concentration. Each stage of grinding was aimed at improving gold liberation. The initial material was ground finer than 1 mm and the gravity tailings were re-ground in rod mills for 30 min for each stage. The final tailing was processed by cyanidation at pH 10.8 to extract any remaining gold. The leaching tailing was washed, dried, quartered and pulverized then analyzed by fire assay.

The second test aimed at comparing the performance of the lab Knelson concentrator with magnetic sluices and classical cyanidation. Two magnetic sluices were tested, the commercial Cleangold® and a homemade magnetic sluice (HMMS), made of polymeric magnetic sheet with field strength of 200 G (similar to fridge magnets). The principle of the magnetic sluice is based on magnetic concentration of magnetite or other magnetic mineral by a ferrite sheet creating a bed on the sluice surface that traps gold. Iron fillings from the hammer or ball mills in the pulp can also form a bed to trap gold. A sample of 10 kg of a ¼ inch crushed sample was ground for 30 min in rod mill to 80% below 0.25 mm (P80 = 0.25 mm) which is a reasonably fine grain size for artisanal gold processing. Subsamples of 2 kg of portions were used to feed all gravity concentration and leaching tests. The gold grades for all tests were similar ranging from 11.50 to 12.60 g Au/tonne. The leaching test was conducted in a rolling bottle at 30% solids with 5 g of NaCN (1 g/L) and 60 g of lime (pH 10.9). The leaching test was conducted for 6 h and activated carbon (AC) was added to the bottle after 4 h of leaching. The AC was recovered by screening and samples of solution, tailing and AC were assayed. The cyanide concentration was checked by titration with silver nitrate in the presence of potassium iodide.

The third test employed the mill-leaching technique. A 10 kg portion of sample crushed below ¼ inch was homogenized and split into 2 kg subsamples. This generated samples with gold grades ranging from 14.7 to 17.5 g Au/tonne. Each subsample of 2 kg was used for a mill-leaching test. Sodium cyanide was added into the mill together with water, ore, lime (pH 10.5) and rods. The grinding time was fixed to 2 h reaching a P80 of 0.105 mm, when the rods were removed and activated carbon was introduced to the mill inside a nylon basket. The mill was restarted and the cyanide slurry

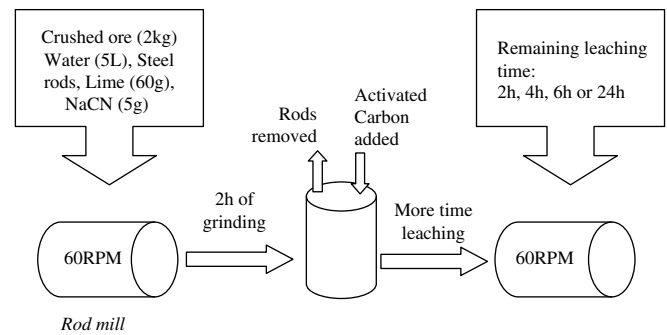


Fig. 4. Lab procedures for mill leaching using the Indonesian sample.

was tumbled inside the mill. The maximum leaching time of a subsample was 24 h (Fig. 4). The leaching tailings were washed, dried, quartered, pulverized and then analyzed by fire assay. The dissolved cyanide in the slurry was monitored by titration with silver nitrate in the presence of potassium iodide.

### 5.2. Results

In the first test it was observed that the gold recovery increased with particle size reduction. In the first concentration stage, with material 80% finer than 0.6 mm, the gold recovery was only 8% and in the final fourth concentration stage, with material 80% finer than 0.07 mm, the accumulated gold recovery was 29%. Cyanide leaching for 24 h extracted an additional 49% of the gold yielding a total Au extraction of 78%. The final tailings grade was 1.49 g Au/tonne and the cyanide concentration in solution at the end of the test was 0.56 g/L.

In the second test, it was observed that the gravity concentration (Table 1) of material with P80 of 0.25 mm was not efficient. The gold recoveries with both magnetic sluices ranged from 7 to 8%, which is quite low, very likely due to poor gold liberation from gangue minerals. Leaching for 6 h extracted 84% of the gold which is at least ten times higher than recovery by gravity concentration.

The results of the third test (Table 2) show that the gold recovery using the mill-leaching process for an ore sample ground for 2 h with cyanide and leached for additional 4 h reached 93%.

## 6. Field tests in Ecuador

### 6.1. Methodology

Cyanidation tests were performed in Portovelo, Ecuador, using two different pieces of equipment available in the region: an agitated tank and a small ball mill called "chancha" that is typically used for amalgamation of concentrates. The use of "chanchas" is beneficial since no additional investment in equipment is necessary to convert to cyanidation. Following grinding in a Chilean mill to 80% passing 0.150 mm, a sluice box was used to pre-concentrate the gold producing a concentrate with grade of 17.3 g Au/tonne. Miners

Table 1

Results of gravity concentration versus rolling bottle cyanidation of the Indonesian sample gold grade (g Au/tonne) [weight, g].

	Cleangold®	HMMS	Knelson®	Cyanidation
Feed	12.60 [1836]	12.30 [1823]	11.50 [1870]	12.20 [1971]
Concentrate	64.00 [25]	117.00 [16]	16.00 [69]	32.00 [24]
Tailings	11.95 [1811]	11.40 [1807]	11.31 [1801]	1.96 [1971]
Au recovery (%)	7%	8%	5%	84%

HMMS = Homemade magnetic sluice.

**Table 2**

Mill-leaching kinetics results for the indonesia sample (Grinding with NaCN for 2 h + Leaching Time).

Leaching Time, h	pH		Final NaCN g/L	%Au Recovered	Au in the sample, g/tonne
	Initial	Final			
2	12.3	12.2	0.88	77.9	14.7
4	12.3	12.2	0.88	85.5	16.2
6	12.1	11.9	0.78	93.1	17.5
8	11.4	11.1	0.88	93.3	15.0
24	10.7	10.7	0.86	93.6	14.8

manually amalgamated 160 kg of this pre-concentrate recovering 26% of the gold.

Miners were very familiar with the conditions of the first test, i.e. cyanidation in agitated tanks. This used a 1.8 m<sup>3</sup> mechanically agitated tank ( $D = 1.2$  m,  $H = 1.6$  m) where 695 kg of pre-concentrate was leached with 5 g/L of cyanide, which is very high but, this is actually half of the concentration of cyanide used by the local miners in this type of operation. Water was added to the tank until the slurry reached 41% of solids. The slurry natural pH was 7. Lime was added to the slurry to reach pH 11. Most miners in the region use precipitation of gold with zinc followed by burning of the zinc. This test intended to show that activated carbon (AC) can be more efficient and avoid toxic zinc vapor emissions. The AC was washed in a 2 mm screen and wrapped in a nylon net and added to the tank after 7 h of leaching.

The second test was conducted using the “chanchas” with 20 kg of steel balls (size ranged from 1/4” to 1 1/2”) to grind 80 kg sample of pre-concentrate grading 17.3 g Au/tonne. The slurry had 70% solids by weight and leaching was performed with 6 g/L of NaCN at pH 10.5. After 2 h of grinding, the balls were removed and 375 g of activated carbon was introduced inside of the mill in a nylon net. Six hours later the test was finished and the activated carbon, filtered solution and tailings were analyzed by atomic absorption in a local lab.

A typical complaint from local artisanal miners is the fact that the elution method to strip gold from activated carbon is complicated. For this reason, miners prefer zinc precipitation. An example of simple stripping process was demonstrated to miners. A 35 L thermo-box (cooler) (Fig. 5) was filled with the 14 kg of gold-loaded activated carbon that was washed with hot (about 90 °C) stripping solution composed of 2 g/L NaCN, 10 g/L NaOH, and 20% of ethanol. Every 2 h the gold-rich solution from the thermo-box was poured on top of 300 g of zinc shavings and new hot solution was introduced into the box. The solution after gold precipitation was warmed in a pan on a gas oven and recycled to the thermo-box. The elution cycle was accomplished in 3 batches (18 h in total).

## 6.2. Results

Following the addition of AC to the cyanidation tank, the gold concentration in solution dropped from 4.33 mg Au/L at 6 h to 2.72 mg Au /L at 12 h and finally to 1.4 mg Au/L at 24 h of leaching. The residual concentration of cyanide in the wastewater was high, 2.1 g/L, indicating an NaCN consumption of 4.5 g/kg of ore. Gold dissolution within 7 h of tank leaching was 62% and the total gold dissolved after 31 h was 94%. The gold grade of the AC was 1235 mg/kg.

The mill-leaching test recovered 95% of the gold after 8 h of leaching (2 h of grinding) which was equivalent to 31 h of agitated tank leaching as performed in the first test. This increase in gold recovery is definitely attributed to the increasing gold liberation due



Fig. 5. Thermo-box used to strip gold from activated carbon.

to grinding. The sodium cyanide concentration in the wastewater was 1.7 g/L and the free cyanide was destroyed with bleach before being discharged. The NaCN consumption was 0.95 g/kg of ore.

The improvised stripping method was also very successful. The thermo-box elution removed 97% of the gold from the AC. The amount of zinc shaving used to precipitate gold from concentrated solution coming from the thermo-box was at least 10 times less than the amount used by the miners in their practices. The loaded zinc shavings were leached with nitric acid and melted with borax to produce the gold bullion. The zinc in the nitric solution was precipitated with lime. Miners in Portovelo do not filter the gold-loaded solution. They let the solid settle and pass the solution over zinc shavings. The main benefit of using activated carbon over zinc precipitation is that only the gold from decanted leach solution can be recovered in the Zn process. All gold remaining in the moisture in the tailings are not recovered. Considering that leaching in tanks is typically at 40% solids (i.e. 60% solution) and the settled solids contain up to 30% moisture, almost 30% of the gold is lost with tailings. Re-pulping followed by settling through multiple stages would lower the gold losses, but they will likely remain to be significant (>10% of gold already leached). Also, zinc precipitation is inefficient for leach solutions that are not de-aerated at room temperature.

## 7. Discussion and conclusions

The gold in the Indonesian ore tested in the lab is fine and more suitable to be leached than to be concentrated by gravity methods such as centrifuge or magnetic sluice concentration. Recovery by using the centrifugal Knelson concentrator was only 9.3%, a very poor result when compared with the cyanidation test, when 93% of the gold was extracted after 6 h of mill-leaching process. This indicates that the artisanal gold miners from Talawaan can easily increase their gold recovery from 30%, currently being obtained when the whole ore is ground in ball mills with mercury, to over 90% by replacing amalgamation with cyanidation in the ball mills. This recommended procedure can eliminate one of the largest sources of mercury emissions in the world which is amalgamation of the whole ore [3].

Grinding in the presence of lime and cyanide is eventually practiced industrially but residence times are typically short [43,44]. Marsden and House [45] mentioned that more than 80% of the gold from some ores can be extracted using the grinding-in-leach process but the cyanide consumption can increase since iron cyanide complexes are formed. For batch grinding, the artisanal ball mills are ideal for cyanide leaching.

The mill-leaching process was successfully implemented in Portovelo, Ecuador. About 95% of the gold was leached from a pre-concentrate (with 17.3 g Au/tonne) obtained by grinding the ore in Chilean mill and concentrates gold in sluice boxes. It was demonstrated that this high gold recovery after 8 h of leaching (2 h of grinding) is equivalent to 31 h of cyanidation in agitated tank as currently is used by the Ecuadorian miners. The direct amalgamation of 160 kg of this pre-concentrate by the local miners yielded a gold bullion of 1.2 g (weight after burning mercury off in a retort). This represents a gold recovery around 26%, the usual recovery achieved by amalgamation.

The mill-leaching process was simple, inexpensive and well accepted by the local miners as it can be implemented without any additional investment in new equipment. Local miners were pleased to see more gold in their hands in reasonable short time (24 h). The main problem in introducing the mill-leaching process is the organization of miners and the division of the work in most mining sites. Not only in Ecuador but also in other countries, miners are not the ones conducting cyanidation in tanks; the introduction of cyanidation in ball mills will upset those Processing Center's owners who invested in manufacturing large cyanidation tanks to leach the residual gold left by the low-performance process of amalgamation.

The mill-leaching process is not a panacea to solve the use of mercury in artisanal mining. However, this procedure requires a minimum knowledge of chemistry and requires a small investment in equipment and reagents (e.g. cyanide, lime, hypochlorite, etc.). In addition, miners must be educated to understand the risks of using cyanidation especially without pH control and proper destruction of the residual cyanide. Tailing management is a critical issue in ASM sites in Ecuador and Indonesia and miners must be involved in the decision process to create tailing ponds. The use of mercury and cyanide in the same processing plant or cyanidation of Hg-contaminated tailings must be definitely banned and strictly enforced by local authorities. Practical concepts of tailing management are badly needed in most of the ASM regions. The mill-leaching results are promising but some investigations regarding the socio-economic and environmental aspects of this alternative must be conducted before introducing the technique in a site.

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