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Research Article

Comparison of Different Gold Recovery Methods with Regard to Pollution Control and Efficiency

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This case study performed at the largest gold mining village in the Philippines compares four methods for gold recovery: amalgamation, cyanide leaching, a shaking sluice, and Cleangold® sluices. The results show that a combination of manual panning or Cleangold® sluices followed by cyanidation is the best solution under present conditions, followed by cyanidation alone. Based on the knowledge obtained, remarks on suitable policy actions, which may be applied also in other gold fields, are made.

Keywords: Amalgamation; Cyanide; Gravity Separation; Mercury; Small-scale Gold Mining

Received: November 14, 2006; *revised:* December 11, 2006; *accepted:* December 16, 2006

DOI: 10.1002/clen.200600024

1 Introduction

Amalgamation with mercury is the dominating method for gold extraction used by 10 million small-scale gold miners (SSGM) in more than 50 countries, resulting in that several hundred to possibly 1000 tons of Hg are annually released into soil, air, and water [1]. The method is stated to be effective [2], in spite of the fact that hardly any studies have been conducted to evaluate its efficiency. Field observations indicate that a substantial amount of gold may be left with the result that the wastes from amalgamation are reprocessed by other methods at several gold fields [3]. At the same time, there is a general idea that amalgamation is impossible to replace by methods less hazardous to the health and environment of miners and residents in areas where gold mining takes place. Actually, Hg free technologies can replace mercury amalgamation technique worldwide, as it did in North America a century ago [4]. The Hg free alternatives are in many cases economically advantageous even without considering the environmental costs of Hg used [5, 6].

Considering the urgency to reduce Hg emissions [7, 8], global Non-Governmental Organizations (NGOs) are advocating a 50% Hg use reduction by 2012 and 70% reduction by 2017, using 2005 as base year [9], while the United Nations Industrial Development Organization (UNIDO) confirms that a reduction of the mercury consumption in the SSGM sector, dominating the intentional usage of Hg, by over 50% until 2017 is achievable [10]. This is a sharper proposed reduction than the present, general decline of Hg use [4, 11], but would be possible to achieve by combining efforts globally, including legislation, binding agreements and information on Hg free alternatives and their advantages for the SSGM-sector and with a more transparent Hg trade.

High gold prices lure miners into the SSGM sector in regions where suitable gold deposits are still available. This will increase mercury demand for use in small-scale gold mining if the present, lavish Hg practices continue. At the same time, gold-bearing placer or alluvial deposits are being exhausted in other areas, forcing many miners to give up mining and others to turn to hard rock

mining, where the technique of amalgamation with Hg, generally, is not feasible [6]. The UNIDO Global Mercury Project estimates that alluvial gold deposits could be as low as 10% of the ores worked by SSGM [12].

Here results from comparative studies are presented of ore processed in the largest SSGM village of the Philippines, Diwalwal. Practiced and alternative gold mining methods in the village are described and evaluated via field experiments and laboratory analyses and compared to the results of experiences obtained elsewhere. Based on the knowledge obtained, remarks on suitable policy actions, which may be applied also in other gold fields, are made.

2 Materials and Methods

2.1 Study Area

In 1983 gold was discovered in a stream of the unpopulated Mt. Diwata, the Philippines [13] and within a few years, the mountain became populated with up to 200 000 persons. The inhabitants of the mining village Diwalwal make their living by extracting gold using Hg amalgamation [14]. In pace with depleted placer deposits, the population decreased by 2005 to an estimated 18 000–20 000 persons, including 4000–7000 miners and well above 1 200 school children [15]. Diwalwal is situated at 8°N, 126°E in Mt. Diwata barangay, Monkayo municipality, 120–140 km to the northeast of Davao City, the capital of Mindanao, the southernmost island of the larger Philippine islands (see Fig. 1). The village is located on steep mountain slopes at the elevation of 600–800 m a.s.l. in two narrow valleys dewatered by Buenas and Balite Creeks into Naboc River, an affluent of Agusan River [15].

The bedrock of the area is early eocene volcanics with up to 1.2 m wide quartz veins, hosting copper containing ores such as azurite $[\text{Cu}(\text{OH})_2(\text{CuCO}_3)]$, copper carbonate hydroxide, bornite $[\text{Cu}_5\text{FeS}_4]$, copper iron sulphide, chalcocite $[\text{Cu}_2\text{S}]$, copper iron sulphide or copper pyrite, besides Cu free minerals such as magnetite and pyrite [15]. The ore is extracted with explosives and manually carried in plastic bags or loaded on hand drawn carriages and pushed out of the tunnels.

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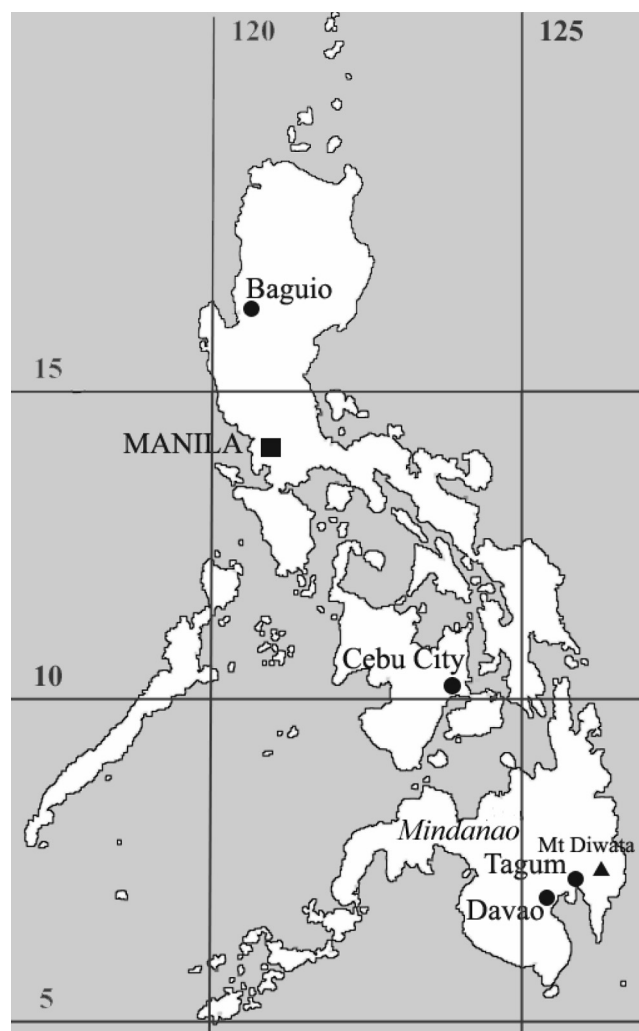


Figure 1. Location of Mt. Diwata and its mining village Diwalwal, the Philippines.

In 2005, up to 7 000 SSGM in Diwalwal were recovering less than 500 kg of gold. The basis for this figure is that the government, in 2003, recovered 41 kg gold on the 15% of extracted ore paid as tax [16]. A minor part of the SSGM does not pay any tax. In 2005, there were 371 establishments with mills [15], each establishment often having more than one ball mill, although rods to reduce the wearing of the drums have replaced the balls. 872 millers [15] are milling and amalgamating the ore. The tailings are then submitted to cyanidation at any of the 71 cyanidation plants.

2.2 Gold Recovery Technologies Studied

In addition to amalgamation and cyanidation, presently used on practically all ore in Diwalwal, ore samples were processed with Cleangold® sluices and by a shaking sluice. All methods studied, including the local methods used for amalgamation, will briefly be described.

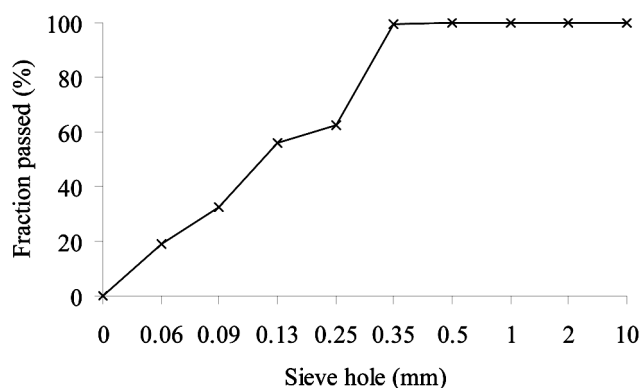


Figure 2. Particle size distribution of the ore sample used for experiments with the shaking sluice.

2.2.1 Amalgamation

The ore is crushed and milled together with water in tumbling mills, so called ball mills, where the balls have been replaced by iron rods in an iron drum (about 2 m × 0.5 m), and rotated by an electrical motor (2.5–3 Hp per drum). After 6–10 h of milling, the particle size is smaller than 0.35 mm and about 60% smaller than 0.2 mm (see Fig. 2).

Verification of the grain size in the field is done by vision and by touch to determine if additional milling time is needed. The slurry is transferred into another iron drum (diameter 0.8 m), called a bubbler (see Fig. 3). About 2 kg Hg is added to 150 kg ore and the drum is filled with water. Before the Hg price increase in 2004, more than twice as much Hg was added to each charge. Inside the bubbler drum, four iron bars are symmetrically located 10 cm from the drum wall along all the length of the drum (1 m). Their purpose is to more efficiently bring the Hg in contact with the ore. The bubbler is rotated with an electric motor for half an hour at about 26–30 rpm and then emptied into a big bucket. Lighter particles are flushed away with a water hose into a dam, awaiting cyanidation, while the amalgam and Hg sink to the bottom. The amalgam and Hg are then poured into a cloth and excess Hg is squeezed through the cloth, leaving amalgam in the cloth. Excess Hg is recovered and reused in the bubbler drum for about two weeks and then discarded, because of changing properties, reducing the amalgamation capacity. The amalgam is heated by a blowtorch, generally in the open, leaving a mixture of gold and silver (between 60/40 and 70/30) with some Hg, typically less than 4%, although the Hg content may in exceptional cases reach 25% [17]. However, the miners at Mt. Diwata are burning off Hg from the amalgam at high temperatures, often close to the melting point of gold (1063°C), so Hg left is generally 0.5–3%. The Hg remaining is driven off when founding ingots at the gold dealers outside Diwalwal, generally in Tagum (see Fig. 1), and to a lesser extent in Monkayo.

Although 50 glass retorts have been distributed for free among the miners in an earlier project, most miners do not use retorts. Gold buyers are by law forced to burn amalgam in a fume chamber with a self-ventilated chimney but without any proper equipment to collect Hg vapor.

2.2.2 Cyanidation

There are five continuous-type Carbon-In-Pulp (CIP) plants in Mt. Diwata using sodium cyanide (NaCN) for leaching gold from the

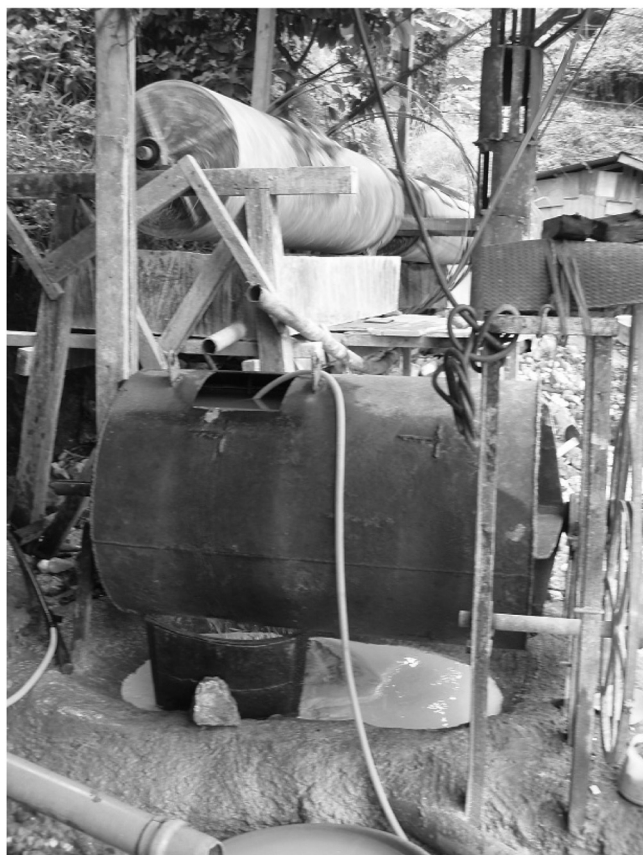


Figure 3. Typical set-up in Diwalwal of ball/rod mills (in the rear) and amalgamation drum, so called bubbler (in the front). Photo: Lars Hylander.

ore. All the other 66 plants using cyanide there are in fact Carbon-In-Leach (CIL) plants, where the ore is leached in batches, although they are locally called mini-CIP plants. This type was studied and will be described.

About 14 000 kg ore, 14 kg NaCN, and 80 kg lime are mixed with water in a 15 m³ tank (see Fig. 4). The ore is practically always pretreated with Hg using the amalgamation method. The slurry or pulp is mechanically mixed and aerated with compressed air for one week, after which 60 kg granular activated carbon, made from coconut shells, is added to absorb the gold dissolved. The pulp is screened, allowing the finely ground ore particles to pass through, but the coarser carbon is captured, dried, and burned to ash. Borax is added to the ash, which is heated in a forge until the gold melts. This is then cooled in water and sold.

2.2.3 Cleangold® Sluices

The principle of the Cleangold® method [18] is to use magnetism to create riffles for a physical separation of gold from grains with lower density, instead of using mercury or other chemicals for separation via chemical reactions. The only equipment needed is a simple sluice (see Fig. 5), through which the gold containing ore and a relatively small amount of water is passed by laminar flow.

To extract the gold, the ore should either contain magnetically susceptible components, or inexpensive, recyclable, magnetically susceptible material can be added. The gold grains settle in the rif-

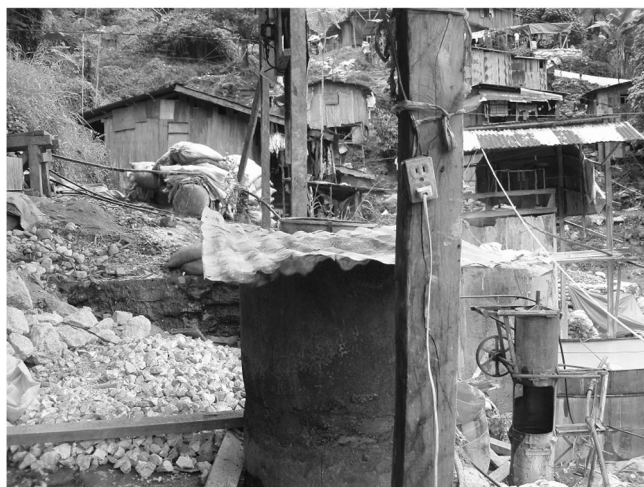


Figure 4. Typical set-up of a small Carbon-In-Leach (CIL) plant, locally called mini-CIP, in Diwalwal, using sodium cyanide (NaCN) for leaching gold from milled and amalgamated ore. Gold loaded activated carbon being burned to ash in the center and an agitated tank for cyanidation in the drum below the roof to the right, behind waste and storing ponds. Photo: Lars Hylander.

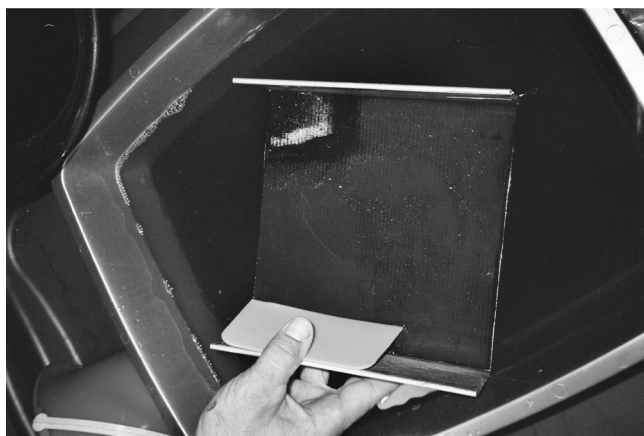


Figure 5. Gold recovered on a mat of iron oxide (magnetite) grains in the upper, left corner of a magnetic sluice from Cleangold®. Photo: Lars Hylander.

fles and then the material attached to the sluice is scraped off into a pan. The final extraction of gold from the gold concentrate in the sluice was done by traditional panning, but can also be done by using strong magnets to remove the magnetically susceptible material from the dry concentrate. The gold grains in the pan can be suctioned up with a small plastic vial or the gold concentrate can be smelted straight away.

Concentrates of Cleangold® sluices used for to recover gold from crushed ore have been assayed with gold values of 2 800 g/ton [19] and even higher, indicating that a directly smeltable product can be achieved. A 0.2 m long Prospector's Sluice (see www.cleangold.com for details) was used in Mt. Diwata in a dynamic mode by operating the sluice with the hands. Samples of ore prepared for assaying using the Cleangold® sluice were extracted in two passes through the sluice.

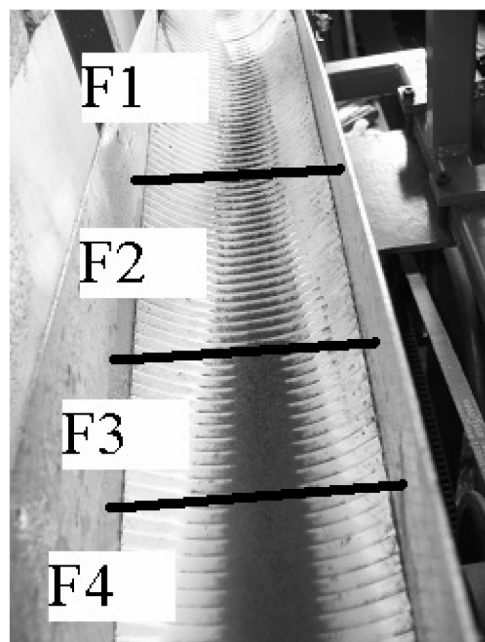


Figure 6. Shaking sluice developed by Yngve Wahlström, Yngves Mekaniska AB, Västerås, Sweden. The ore is added at the upper end of the sluice and water flushes it downwards while the shaking movements of the sluice are transporting heavy grains upwards, towards the water current. F1–F4 are fractions sampled as explained in Tab. 2. Photo: Lars Hylander.

2.2.4 Shaking Sluice

Ore samples from Mt. Diwata were also run on a prototype of a 0.9 m long shaking sluice, also called shaking table, recently developed by Yngve Wahlström, Yngves Mekaniska AB, Västerås, Sweden (see Fig. 6). From its lowest point, the sluice has a gentle inclination for 0.2 m in one direction and for 0.7 m in the other direction, leading to its highest point, where a water inlet is placed. At the other end, light particles are flushed out of the sluice by water flow, while the shaking movements are transporting heavier particles towards the highest point counter current to the water flow, which is in contrast to other shaking sluices [20]. The bottom is covered with a plastic mat with 2.5 mm deep, V-formed riffles with a centre-to-centre distance of 7 mm. The sides of the riffles facing the water flow have an inclination of 90 degrees.

At the start of the experiment, the shaking (590 cycles min^{-1} with 10 mm maximal deflection) and the water flow were turned on and the water flow was adjusted to 30 L min^{-1} according to experiences from earlier experiments. The ore sample was mixed with water, forming a slurry, and then poured into the sluice with the remaining bottom sediment added to the sluice by spooning. After five minutes, the shaker and the water were turned off simultaneously. Water was drawn away from the riffles via capillarity using a piece of paper placed beside the material without touching the ore material, which had been separated into clearly visible fractions along the sluice. Each fraction was quantitatively scooped up and dried at 50°C for two weeks before being analyzed.

2.3 Sampling and Analyses

Raw and processed ore samples were kept in humid conditions until the conclusion of the processing experiments in the field and

laboratory to avoid oxidation of sulphides and formation of rust with related aggregation. Before analyses, the samples were dried at 50°C for microscopical analyses and at 103°C for other analyses. Total gold analyses were determined by fire assay followed by mass spectroscopy. The sample was melted in a clay crucible with fluxes (silica and borax), litharge (PbO) and a reducing silver inquart. The lead oxide was reduced to lead, which dissolved the precious metals and formed a metallic layer at the bottom of the crucible. The lead was then heated under oxidizing conditions to eliminate it and remaining metals were dissolved in boiling nitric acid. The final analysis was done on an Elan 6000 ICP-MS [21]. These analyses and related experiments were run in 5 replicates and most other analyses and experiments in triplicate. Laboratory reference material analyzed repeatedly gave a relative standard deviation of 1.3% for elemental analyses.

Inspection with a light microscope was used to identify and examine gold and other mineral particles and their characteristics. Morphological characteristics studied included particle shape (rounded, elongated, irregular, folded, etc.), particle size range, presence and simple percentage of minerals and free metals other than gold, crystalline characteristics (optically flat surfaces, twinned or multiple crystals, and straight edges not created by fracture), surface irregularities (scratching, amalgamation, oxides, traces of gangue material, fractures, holes, clusters), and general color (rough determination of purity of gold and possible surface oxidation).

The samples used for photomicrography were mounted in water and covered with a cover slip or mounted in MeltMount™ permanent mounting media. Lighting was by unidirectional top lighting with a balance background lighting provided by transmitted light. The photomicrographs are at a nominal magnification of 40X or 100X and they were all taken by David Plath using a Nikon Optiphot Pol microscope, using 35-mm film format. Samples from the shaking sluice were panned to get a concentrate of high-density particles for characterization with the microscope. In some cases, a magnet was applied to the prepared slide to determine the presence of magnetic minerals. Following characterization, each panned sample and slide material was returned to the source bag and the handling equipment was cleaned before proceeding to the next sample.

3 Results and Discussion

3.1 Gold Recovery with Amalgamation and Cyanidation

Gold recovery from the Mt. Diwata ore is quite poor using the amalgamation method (Table 1). Several factors contribute to this. Firstly, the gold is occluded in different minerals, mainly sulphides which must be ground to recover the gold. The miners state that gold recovery when amalgamating ore from Mt. Diwata is always below half, generally 25–35% as compared to the 10% demonstrated in this study (see Tab. 1). It is possible that the “average” ore that the miners based their estimate on differed from our ore in that ours might have originated from a more highly weathered part of the deposit where oxide coatings can interfere with the amalgamation (see below) or that the gold particle size was finer in our samples than generally seen. This would decrease gold recovery by amalgamation, because Hg cannot efficiently amalgamate gold particles below 0.07 mm [22].

Table 1. Gold content in unprocessed ore and after Cleangold® sluicing, amalgamation, and cyanidation, respectively, and percentage gold recovered. Diwalwal, the Philippines, 2004.

	Average	SD	RSD	n	Gold recovered
	mg/t	mg/t	%		%
Original ore	7938	834	10.8	5	–
Cleangold®	4540	579	15.7	5	42.8
Amalgamation	7147	1389	16.7	5	10.0
Cyanidation	400	125	44.6	5	95.0

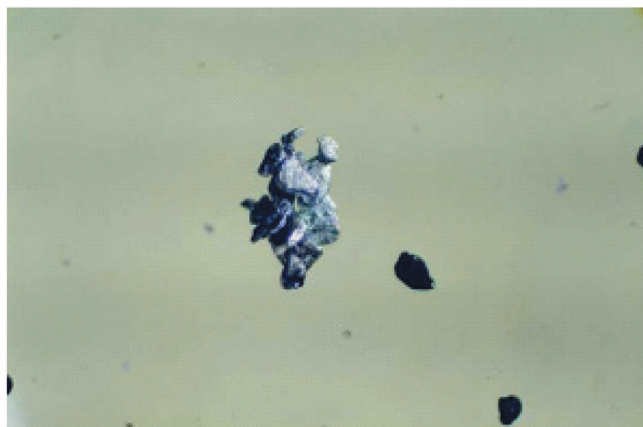


Figure 7. Amalgamated fine gold particle clusters, Saramacca River, Suriname (40X nominal magnification). These clusters were found in all tailings where mercury was used in the process. The high surface area in relation to volume of these clusters makes them more mobile and thus more easily lost.

In contrast, cyanidation needs fine grains (<0.2 mm) [22]. Although about 40% of the milled grains were a little larger than 0.2 mm (see Fig. 2), the gold grains present were below this size as demonstrated with microscopical analysis in section 3.3. Tab. 1 indicates that the cyanidation was efficient in this case, recovering 95% of the gold present and thereby exceeding the generally achieved 90% recovery. A process dissolving the gold, such as cyanidation, requires fine particles to bring the gold into solution within a reasonable time. This is in contrast to amalgamation, where surface reactions result in gold grains being agglutinated rather than dissolved in Hg (see Fig. 7). This also is in agreement with observations from dental fillings. Gold fillings acquire Hg from adjacent amalgam fillings forming a surface layer on the gold but without penetrating deep into it.

As a result, amalgamation is only effective on gold grains with a particle size of 0.07–1.5 mm [22]. Smaller grains may not get wetted by Hg due to the high surface tension and negative capillarity of Hg. If they eventually get dispersed in liquid Hg, they will not be brought so close to each other that they can adhere into an amalgam lump but can pass through the fabric, dispersed in the excess Hg pressed out. At locations with a large fraction of fine gold particles in the ore, the gold content of used Hg is so high that the Hg sellers are making a better profit on recovering gold from used Hg than from selling Hg to the miners. This is the case at Kalimantan, Indonesia, where the Hg sellers provide the miners with Hg for free and encourage them to use it liberally and to hand the used Hg back to the sellers after that the miners have processed it to get an amal-

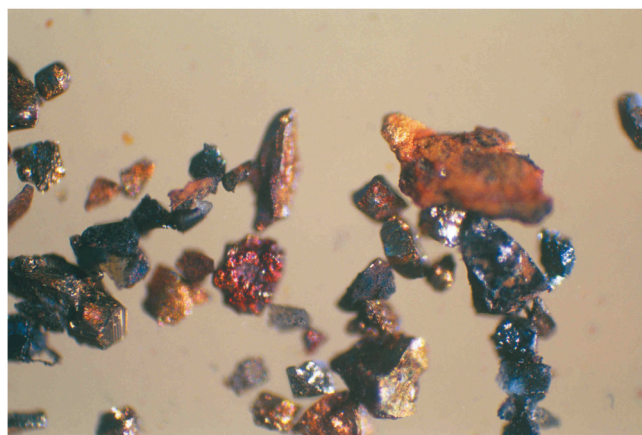


Figure 8. Magnetic fraction recovered with a magnet from Mt. Diwata ore. Note the particle of gold emerging from the ferrous particle to the upper right of centre. (100X magnification.)

gam ball by squeezing it through a piece of fabric [23]. According to anecdotal information, the Hg sellers are cooling the used Hg with ice and then processing it in the same way as the miners. Using fabric or filters with finer holes would be an alternative method for the miners, which could reduce the gold content in used Hg to levels which would eliminate the basis of the Hg sellers' exploiting policy and lavish Hg practice of less informed miners.

The miners at Mt. Diwata state that adding less Hg (> 50% reduction due to an increased Hg price in 2004) has not reduced the gold recovery, but reduced their Hg consumption markedly. This may seem illogical, because it is not in agreement with general chemical mass reactions, where adding more of a reactant in deficit will change the previous equilibrium, resulting in a larger quantity of the product formed by two reactants. However, the miner's observations indicate that the low gold recovery of amalgamation is not due to lack of Hg for the amalgamation, and further reduction from the present 1000:1 Hg: Au ratio may be possible without reducing recovery. Even if adding more Hg to the ore containing large amounts of fine gold reduces the amount of gold left in the tailings, the fine gold will still be lost by the miners as it passes through the pores of the fabrics used (about 0.05 mm) to collect the amalgam together with the excess Hg, as addressed above.

In addition, gold attached to other minerals cannot be recovered by amalgamation. Despite the finely milled particles, there was gold still not fully liberated (see Fig. 8). Another reason for poor bonding between Hg and gold in the Mt. Diwata ore is that many gold grains have oxidized surfaces (see Fig. 9). It takes very little oxide to prevent a particle from being amalgamated.

Fig. 10 is taken of a sample that was in intimate contact with free mercury from gold extracted in Suriname, South America. In this sample some of the gold looks very clean and yet could not be amalgamated. Oxides at the surface are not a problem when gold is oxidized and dissolved in an alkaline cyanide solution. However, gold molecules contained within the crystalline structure of sulphide minerals such as pyrite and arsenopyrite demands special treatment so that the gold is exposed to the cyanide and is subsequently dissolved.

There are different methods to break sulphide bounds such as roasting and bacterial oxidation, which aim to improve the extractability of gold. Just exposing the sulphide ores to air will cause

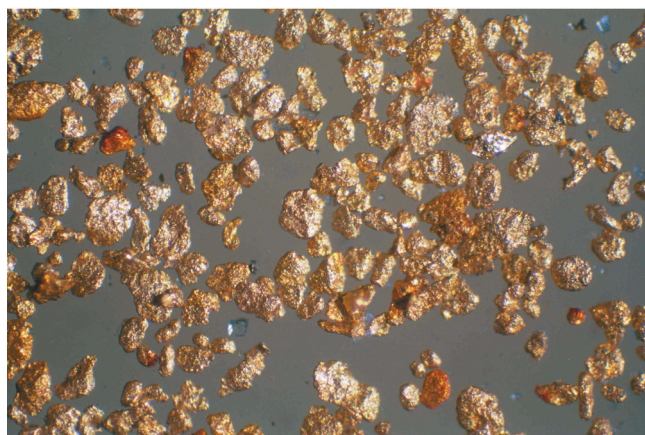


Figure 9. Photomicrograph of gold grains from Mt. Diwata with oxidized surfaces. Note the variety of colors in this predominately gold sample. The relatively light colour of the bulk of the gold is probably due to the presence of silver in the alloy. The red and yellow oxide layers on some of the gold are representative of gold that has been in a highly weathered deposit. (100X magnification.)

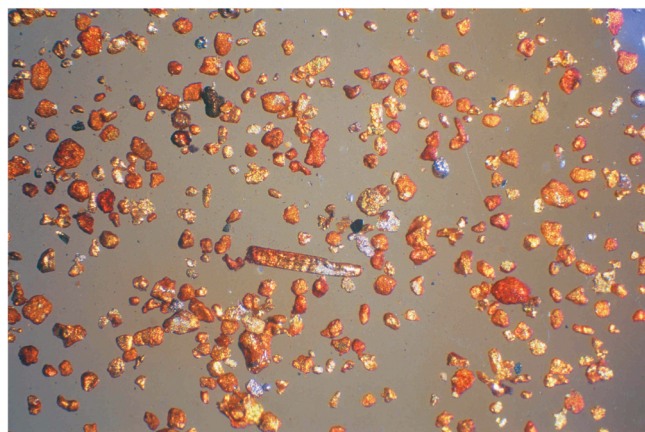


Figure 10. Alluvial gold from Suriname that could not be amalgamated. Note the variety of oxide colours, probably a result of different thicknesses of oxide layers generated by weathering. (100X magnification.)

them to begin to degrade to sulphates. This process is too slow to rely upon when recovering gold, but points out an additional environmental problem when mining sulphide ores, which results in acidification and related pollution of surface and groundwater. These ores should never be mined for processing by amalgamation anywhere, because the large portion of gold left behind will result in reprocessing with other technologies creating additional environmental and health problems.

3.2 Gold Recovery with Gravimetric Methods

Two gravimetric methods were tested with ore from Mt. Diwata: the Cleangold® Prospector's Sluice and a shaking sluice. These preliminary studies were done without enough time and resources to optimize running conditions. Nevertheless, the Cleangold® Prospector's Sluice demonstrated gold recovery rates exceeding amalgamation, in spite of the fact that amalgamation has been adapted to the actual ore type for two decades (see Tab. 1). The Cleangold® sluice



Figure 11. Example of Cleangold® test system (front) replacing copper amalgamation plates seen in the background at a hard-rock ore operation in Suriname, where the ore is prepared with a hammer mill. Assaying of a sample of the concentrates from the first of the four sluice inserts used showed almost 14 000 g gold/ton after a 24 h period of use. Photo: Kristina Shafer, www.artminers.org.

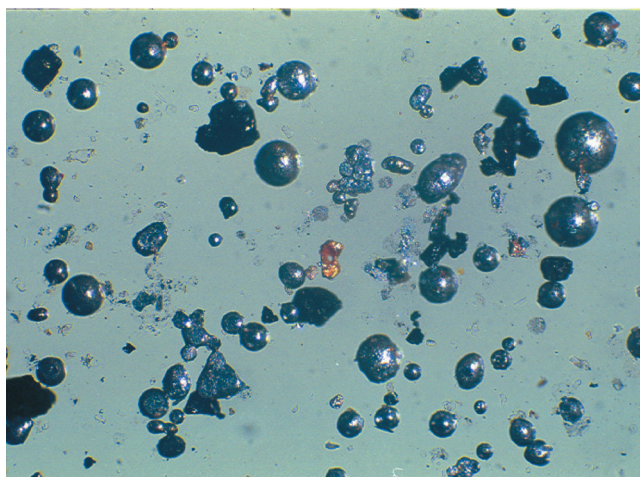


Figure 12. Photomicrograph of gold, amalgamated gold, and free mercury recovered from a Cleangold® sluice used in Suriname (100X nominal magnification). The gold particle in the centre is 70 microns in its longest dimension.

was operated by hand in a dynamic mode, while scaled up static methods employing larger Cleangold® sluices and allowing the processing of large amounts of ore (see Fig. 11) generally show higher recovery percentages and better recovery of even finer gold (down to 0.005 mm) than was seen in this study. With an appropriate pump for the milled slurry, processing the ore with Cleangold® sluices can be done with less manpower than the amalgamation method. A second or third passage of the slurry results in an improved recovery and can be achieved by adding additional Cleangold® sluices to the separation system, which requires no additional manpower.

In addition, mercury broken down to particles less than 5 microns in diameter by the passage of alluvial ore spiked with mercury through a gravel pump has also been successfully recovered with simple Cleangold® modifications preventing its loss to the environment with the process tailings (see Fig. 12).

