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Research Article

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

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.

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 volcaniclastics with up to 1.2 m wide quartz veins, hosting copper containing ores such as azurite $[Cu(OH)_{2\cdot2}(CuCO_3)$, copper carbonate hydroxide], bornite $[Cu_5FeS_4$, copper iron sulphide], chalcopyrite $[CuFeS_2$, 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.
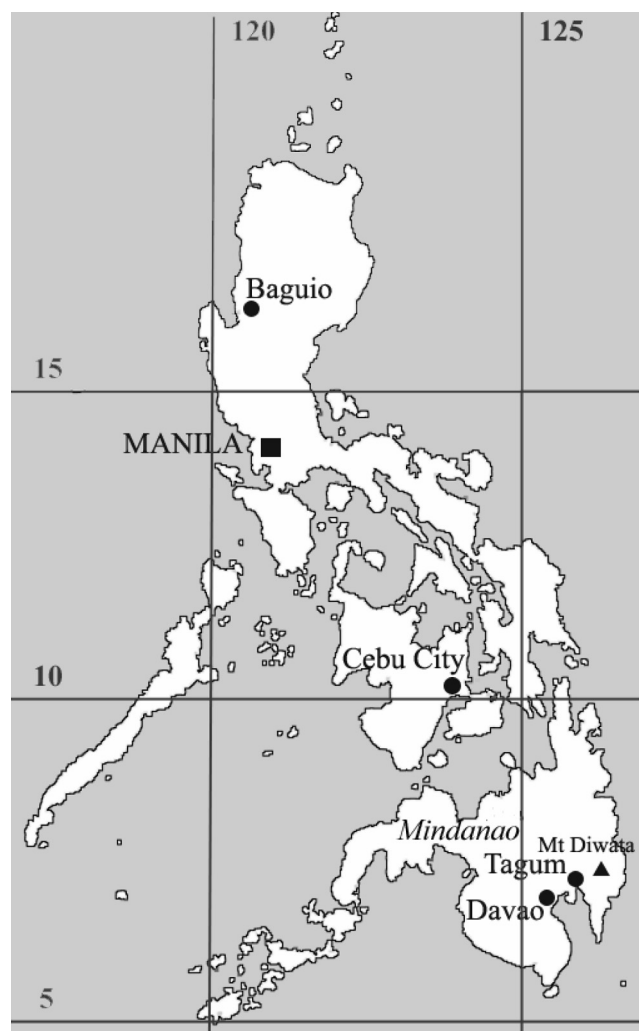
Figure 1. Location of Mt. Diwata and its mining village Diwalwal, the Philippines.

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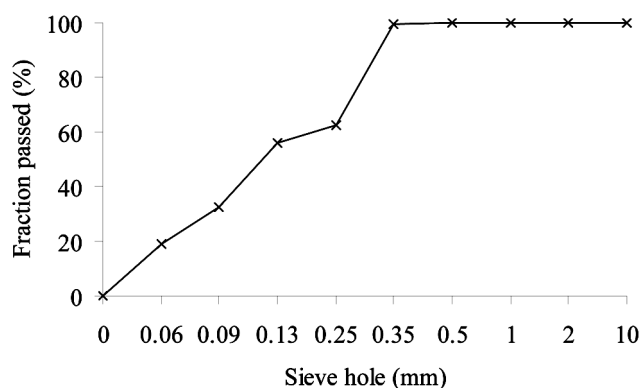
Figure 2. Particle size distribution of the ore sample used for experiments with the shaking sluice.
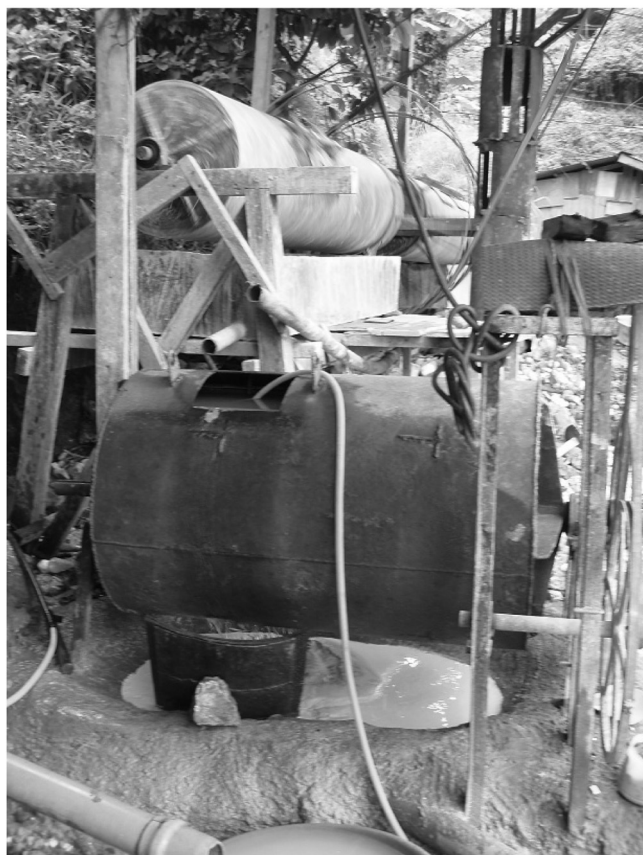
2.2.1 Amalgamation

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 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.

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.
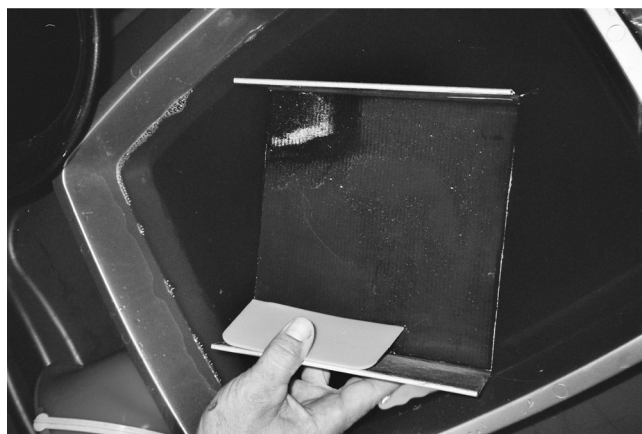
Figure 5. Gold recovered on a mat of iron oxide (magnetite) grains in the upper, left corner of a magnetic sluice from Cleangold®. Photo: Lars Hylander.
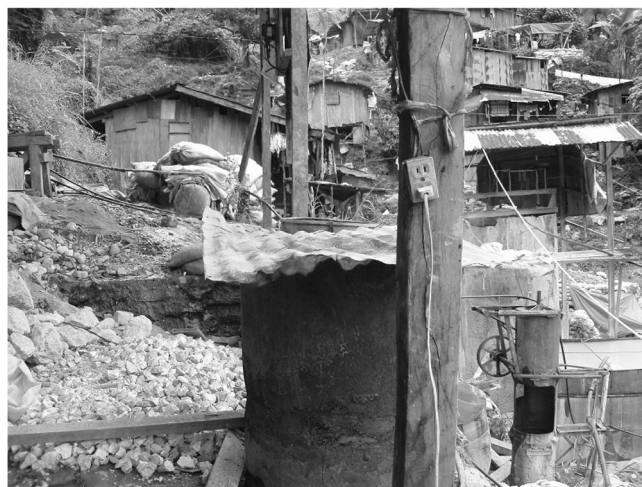
ore. All the other 66 plants using cyanide there are in fact Carbon-In-Leach (CIL) plants, where the ore is leached in batches, although they are locally called mini-CIP plants. This type was studied and will be described.

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-

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.
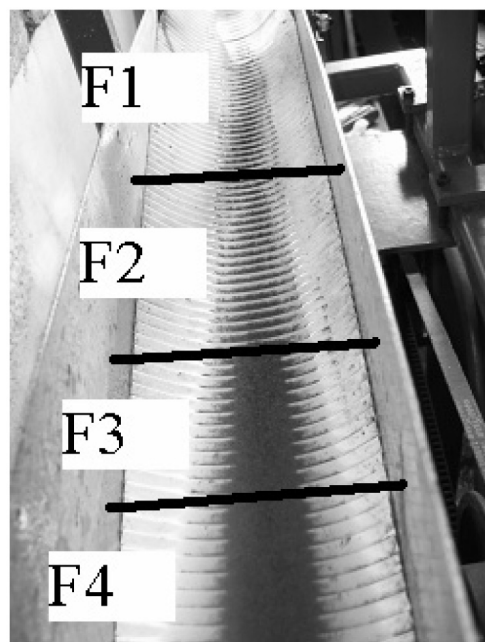
Figure 6. Shaking sluice developed by Yngve Wahlström, Yngves Mekaniska AB, Västerås, Sweden. The ore is added at the upper end of the sluice and water flushes it downwards while the shaking movements of the sluice are transporting heavy grains upwards, towards the water current. F1–F4 are fractions 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 grounded 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-
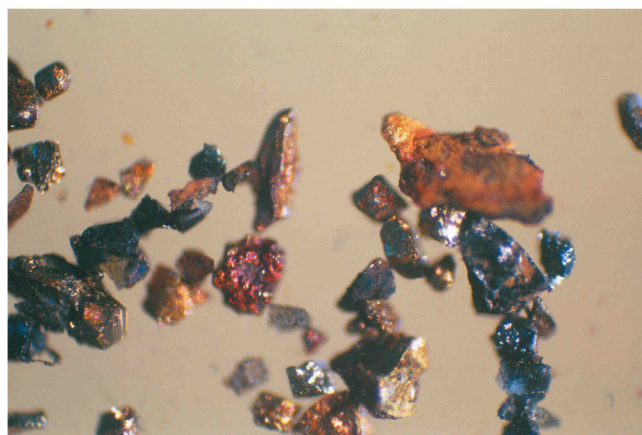
Figure 8. Magnetic fraction recovered with a magnet from Mt. Diwata ore. Note the particle of gold emerging from the ferrous particle to the upper right of centre. (100X magnification.)

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.
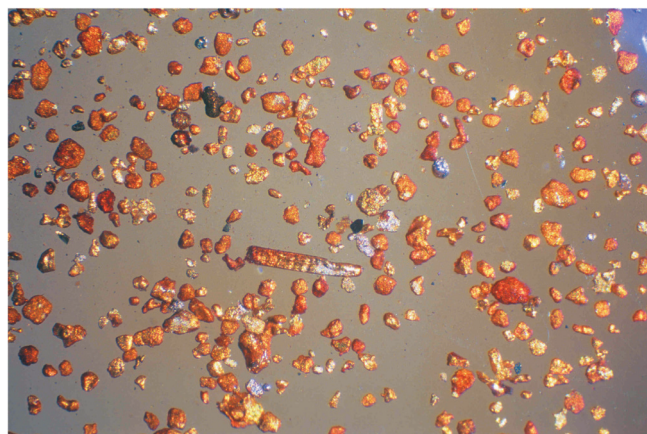
Fig. 10 is taken of a sample that was in intimate contact with free mercury from gold extracted in Suriname, South America. In this sample some of the gold looks very clean and yet could not be amalgamated. Oxides at the surface are not a problem when gold is oxidized and dissolved in an alkaline cyanide 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
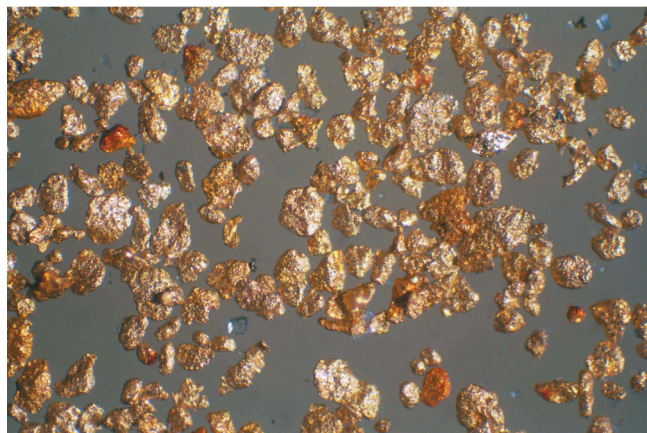
Figure 9. Photomicrograph of gold grains from Mt. Diwata with oxidized surfaces. Note the variety of colors in this predominately gold sample. The relatively light colour of the bulk of the gold is probably due to the presence of silver in the alloy. The red and yellow oxide layers on some of the gold are representative of gold that has been in a highly weathered deposit. (100X magnification.)

Figure 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 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.)

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.
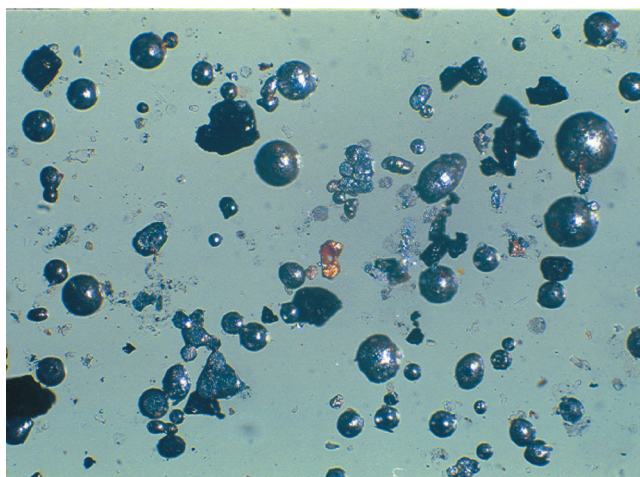
them to begin to degrade to sulphates. This process is too slow to rely upon when recovering gold, but points out an additional environmental problem when mining sulphide ores, which results in acidification and related pollution of surface and groundwater. These ores should never be mined for processing 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

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).
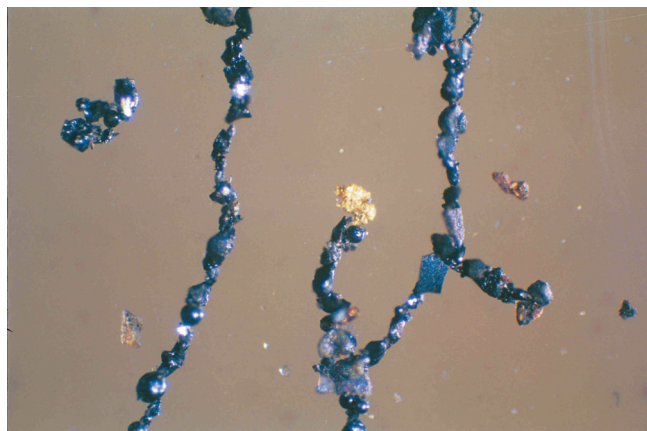
Figure 13. Magnetic fraction recovered from sample I-F5 shows the variety of magnetic materials present in the milled ore, from natural ore particles, to scale particles, and welding slag particles.

3.3 Results from Microscopical Analysis of Samples from the Shaking Sluice

Manual panning of crushed and milled ore from Mt. Diwata resulted in separation of about 95% colorless or white mineral and about 5% "gold colored" sulphides, so called "fool's gold" such as pyrite and chalcopyrite. A few gold particles were noted. There is a large fraction of magnetic material in milled ore from Mt. Diwata. The magnetic fraction, recovered from the milled ore with a magnet, consists of predominantely black magnetic mineral grains with some highly magnetic irregular oxidized ferrous "clumps" (see Figs. 8, 13). A crystalline silver colored particle was noted as well as a gold particle that was not fully liberated from the matrix mineral.

Overall, the minerals had the appearance expected of crushed ore with some particles showing concoidal fractures and others showing pure crystalline forms, including cubic forms and striated facets expected of sulphides. Magnetic particles originate from the ore as well as from wearing of the rods during milling and welding slag particles.

When the ore was run in the shaking sluice, five fractions were discerned and collected (see Fig. 6), where F1 is the fraction from the uppermost area of the sluice, F2−F4 sampled when moving downwards in the sluice and F5, expected to be the lightest material, leaving the sluice at its lower end. Separation and characterization was done in triplicate, indicated with Roman figures I−III before F. Sample I-F1 was a 50/50 mixture of "gold colored" and low density but large in size, white or colorless particles. Samples II-F1 and III-F1 had white or colorless particles up to 95% (see Tab. 2). There was a trace of magnetic minerals. Several particles of free mercury around 20 microns in diameter were noted as well as several particles of gold 20−30 microns in the longest dimension (see Fig. 14, Tab. 2). The gold was mostly equant (see Fig. 15). Characterization of the gold found was consistent with alluvial gold. No evidence of the method of sample preparation was noted on the surface of the gold other than the degree with which it was freed from the gangue material.

The major difference between fractions F1 and F2 was that F2 had a lower share of sulphides (see Tab. 2). Sample I-F3 had about 90% low-density colorless or white minerals and about 10% "gold colored" minerals (see Fig. 16). A trace of free mercury was noted as well as a few particles of amalgamated gold about 30 microns in the longest dimension. The gold was, again, mostly equant. Evidence that minerals were not fully liberated by the grinding was seen.

Sample I-F4 was easily separated by panning into fractions of colorless or white minerals (about 90%), "gold colored" sulphides (about 10%), and about two thousand free gold particles (< 1% of the sample). This was the first fraction that had a substantial amount of gold present and it was quite easy to separate it from the "gold colored" sulphides for mounting. The gold ranged in size from 20–180 microns in the longest dimension. About 10% of the gold showed visible oxide staining on the surface similar to that seen on gold from heavily weathered alluvial gold deposits previously studied in Suriname (Figs. 9, 10). From work done on those samples, it is suspected that these oxide layers prevent the gold from being amalgamated. A few particles resembling amalgamated gold were also noted and it was suspected that these could also be native silver. These "silver colored" particles are in the minority and no partial amalgamation of gold particles was seen, thus lending credence to the possibility of the presence of native silver.

Sample I-F5 was mostly low density, colorless or white minerals with a small amount of "gold colored" sulphides mixed with free gold (see Tab. 2; Fig. 17). Some free mercury and amalgam was noted. Hundreds of gold particles were seen, mainly in the size

Table 2. Weights of Mt. Diwata ore fractions obtained with the shaking sluice, estimated sulphide percentage and important observations on microscopical characterization of gold particles.

Fraction	Location in sluice	Average weight g	SD g	n	Sulphides %	g	Comments on gold particles
F1	top of sluice down to first red frame crossing the sluice	1.5	0.1	3	50-90	1.03	Few, equant, large.
F2	second next to top down to the part with standing water	3.0	0.7	3	20–25	0.61	Very few, equant.
F3	upper part of the standing water in the sluice	5.5	1.5	3	5-10	0.44	Few, mostly equant, 30 µm.
F4	lower part of the sluice with deeper standing water	37.0	2.6	3	<5-10	2.51	Many, both equant and flat, 20–180 µm.
F5	the material leaving the lower part of the sluice	25.2	4.7	3	<1	0.28	Many, predominately flat, 30–200 µm.
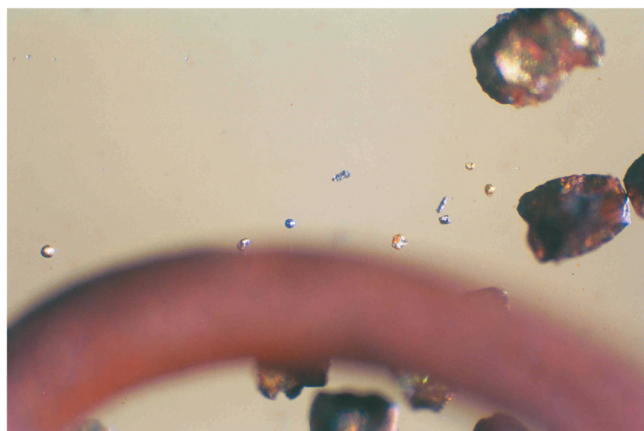
Figure 14. Photomicrograph of I-F1 fraction. Note the gold, free mercury and amalgamated gold above the large piece of copper wire that was present in the sample. (100X magnification.)

Figure 16. Example of the sulphide and matrix minerals in the sample I-F3. (40X magnification.)
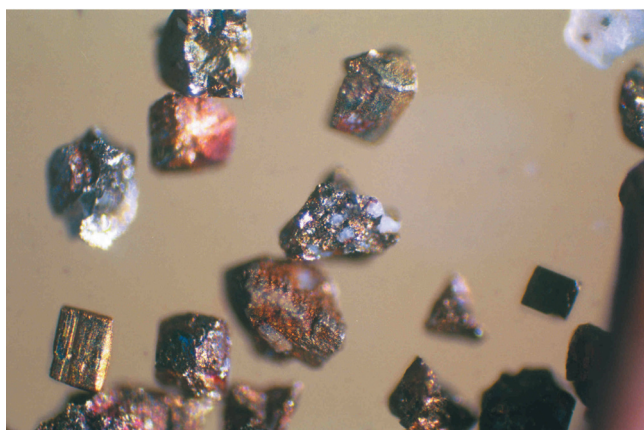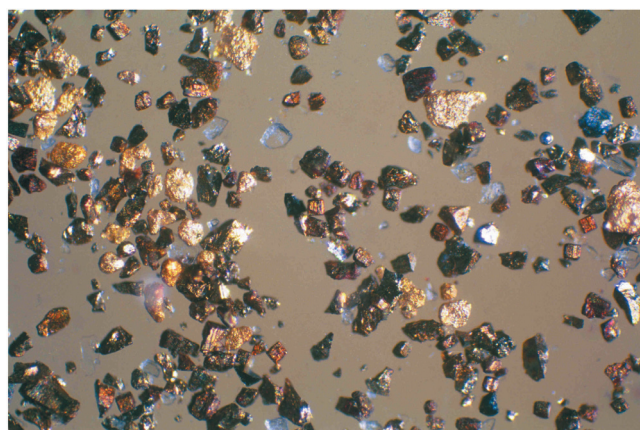

Figure 15. Subsample of I-F1 with a particle in the centre showing mixed minerals not fully liberated by the grinding process and a crystalline pyrite particle in the bottom, left corner as evidenced by the surface striations. (100X magnification.)

Figure 17. Example of the sulphide and matrix minerals in the sample I-F5. Note the amount of gold in this sample from the tailings. (100X magnification.)

range of 30–150 microns, some up to 200 microns in the longest dimension. The shape of the gold particles in these samples is starting to trend to the more predominantely flat particles. The larger particles were very flat and thin. The replicates of fractions 4 and 5 differed significantly from I-F4 and I-F5 with respect to in which fraction most gold particles were found. This was in F4 for replicate I, in F5 for replicate II, while for replicate III there was about the same number of gold particles in F4 and F5.

The amount of gold that was present in the tailings of this process was unexpected with gold present also in I-F5, the tailings replicate having the smallest losses. The shape of the gold plays a large part in the ability of any gravity separation to capture these particles and while most of the gold was captured early in the process, the material that was lost was in some cases the largest particles seen (200 microns in the largest dimension). Generally, well-run gravity separations will capture gold down to about 150 microns in large-scale operations employing expanded metal and looped carpet sluices. The addition of energy in the form of a shaking table appears to exacerbate the losses of the flatter particles even on this small scale. Even if it is possible that these losses were a result of the

small sample sizes being run and that under normal operation, a continuous mineral slurry would prevent some of the loss, small particles (typically below 0.002 mm) will hardly precipitate at all, and common soil mineral particles up to around 0.05 mm need several minutes to precipitate in stagnant water [24], while high density particles, such as gold and platinum in the 0.02–0.05 mm range may in stagnant or laminar flowing water settle in less than 5–10 s. Therefore, energy added via shaking movements as well as unintentional vibrations and turbulences in the water flow has a tremendous influence on the successful separation of gold in sedimentary technologies. Densities of the solid particles are material specific and the density of water is given, although in large-scale mining operations it may be adjusted by adding chemicals. The equilibrium point of factors determining whether a fine gold particle will settle or stay in suspension is, therefore, restricted to a fairly narrow range, calling for careful monitoring of sluices when the majority of gold particles are fine, if gravimetric methods are at all possible. However, as easy as it was to recover the gold from these samples with a simple gold pan makes one wonder if the added expense of a shaker table in this case is warranted for small-scale miners. In case

a complex infrastructure should be set up for this type of ore encountered in Mt. Diwata, chemical dissolution of the gold particles is the only efficient technology presently known. With such technologies, the gold particle fineness and the large surface area: weight ratio enhances the dissolving efficiency.

The ore is milled to release occluded gold grains. Gold particle size in the milled ore appears to be the particle size actually encountered in the virgin ore of Mt. Diwata, and is hardly influenced by the actual milling. Since gold is malleable, it absorbs the energy that is crushing the other ore particles and there was rarely any evidence of milling on the fine gold grains, demonstrated by the fact that the oxide coatings stayed intact through the milling process. The gold particles are alluvial in nature. A few larger gold grains encountered, which were flat (see Tab. 2; Fig. 17), had been flattened before they became entombed in the alluvial ore.

Free mercury was seen in several of the samples as well as amalgamation of some of the gold present. The ore was bought from the actual miner, who represented it as virgin. No Hg was added to the mill during milling and the ore was submitted to amalgamation after it had been sampled. It was not possible to evaluate where the ore had been contaminated with Hg. It might have been by Hg retained inside the liner from earlier batches, residues of previous amalgamation, or from unintentional contamination during crushing since the mills are not cleaned carefully between the batches because it is too time-consuming. Since Hg covers the gold surface and dissolves more slowly in cyanide than gold does, Hg contaminated ore as well as tailings from amalgamation reduce the amount of gold recovered by cyanidation. Drying the samples at 50°C may have resulted in the loss of some of the mercury given the exceptionally fine size (<30 microns in diameter). Drying was done to correctly determine the dry sample mass and was not needed for the purposes of microscopical characterization such as this. The drying can, therefore, be done at air temperature or not at all for practical field applications of microscopy at the mine, since the presence of some moisture in the samples does not create a problem.

4 Concluding Remarks Including Socio-economic Aspects

Amalgamating the ore of Mt. Diwata results in low recovery of gold and reduces gold recovery from subsequent cyanidation. Gravity separation without adding energy via sluice movements can separate a larger portion of gold from the ore than amalgamation. Therefore, a combination of manual panning or Cleangold® sluicing followed by cyanidation is the best solution under present conditions, followed by cyanidation alone.

Cyanidation is not a panacea, but cyanide is biodegradable to common compounds with essential elements and, therefore, does not cause future damages due to bioaccumulation, contrary to Hg. Most other methods bringing gold into solution are even more hazardous than cyanidation [25], although the iGoli Process may be an exception, using sodium hypochlorite solution (bleach) for leaching gold in an acidic medium and precipitating it from solution with sodium meta-bisulphite [26]. However, chlorine in the form of bleach is of environmental concern because of the formation of comparatively stable trihalomethanes (THMs) and haloacetic acids (HAAs). These organic compounds have carcinogenic and other health damaging effects [27, 28].

The Environmental Protection Agency has lowered the accepted level of these compounds in the water supply to 0.08 and 0.06 mg L^{-1}

for total trihalomethanes and a sum of five haloacetic acids, respectively [28]. This should be considered when evaluating the recently announced gold recovery method from Haber Inc., using "nontoxic" leaching chemicals [29].

The presently practiced gold extraction methods, where mercury amalgamation is followed by cyanide leaching, result in two serious health and environmental hazards, which need to be tackled in different ways. Since amalgamation cannot be supported from any economic standpoint in Mt. Diwata as well as in many other gold fields in Brazil, China, Ecuador, Indonesia, Peru, Philippines, Tanzania, Venezuela, and Zimbabwe, where amalgamation is followed by cyanidation [2, 3], there must be structural and social contexts hindering the immediate termination of its use. Efficient recovery of gold present in the ore at the first processing removes inducements for reprocessing the mining wastes in the future with associated environmental degradation. Cyanidation of the raw ore would improve gold recovery compared to the present combination of methods practiced and also reduce manpower and extraction costs. These savings should be geared towards the investment in better and safer equipment than that presently used for cyanidation in, e.g., Mt. Diwata. To initiate this transition to less hazardous gold mining, loans to invest in safe and efficient gold extraction technology should be made available to responsible SSGM:s worldwide, eventually organized in cooperatives. Organizing the SSGM:s is itself a challenge, demonstrated by the fact that of several amalgamation centers established in Venezuela in the 1990's [7], none was still in operation in 2001. Nevertheless, any further efforts to establish common processing centers for SSGM should employ more suitable technologies than amalgamation.

It should also be realized that well-informed miners would hardly combine amalgamation with cyanidation. Actual conditions demonstrate a severe problem, which is not mainly caused by illiteracy or poor education and occasionally with an additional barrier to learning by brain impairment due to the use of Hg, but rather a general lack of interest worldwide to transmit proper knowledge to and develop suitable technologies for the SSGM sector.

The present, general decline in Hg demand globally may be accelerated by binding agreements on trade restrictions for Hg from industrialized countries and political guidance of the SSGM-sector. This is justified through environmental costs that are not included in present market prices of gold extracted with Hg. The challenge is to convince individuals, groups, and countries such as the USA and China, profiting from present usage and emissions of Hg, to take responsibility to improve living conditions in other parts of the world.

A higher price paid to the miners for gold recovered using environmentally sustainable methods would be another option to economically convince miners to refrain from using Hg. Gold recovered without using mercury or harmful chemicals such as cyanide can inexpensively but reliably be distinguished with a light microscope [6]. With an appropriate certification system, this gold could then be conveyed to jewellery consumers who are aware of the environmental damages caused by Hg used for gold extraction and are, therefore, prepared to pay a higher price. National and International authorities may even consider subsidizing gold produced in an environmentally sound way in order to mitigate future costs caused by damaged health and environment. Subsidies are often deemed as bringing more negative effects than positive and this is the case regarding subsidies for mining mercury [4], but subsidies to compensate for costs not included in the current market price are justified.

5 Summary

The results show that the amalgamation method is presently used on all ores, in spite of gold recovery rates of 10−35% of initial gold content of the ore. The low recovery is caused by several factors, such as small and occluded gold grains and gold grains with oxidized surfaces that do not amalgamate as documented by light microscopy and photomicrographs. The miners realize that their recovery is low and are sending all amalgamated ore tailings for cyanide leaching, which was the most efficient of the methods studied, recovering up to 95% of initial gold content. The Cleangold® sluices recovered more gold than amalgamation, although gravimetric methods have limitations on the actual ore. Therefore, a combination of manual panning or Cleangold® sluices followed by cyanidation is the best solution under present conditions, followed by cyanidation alone.

Transition to less hazardous gold mining could be facilitated with loans for investment in safe and efficient gold extraction technology, information and practical training of the miners combined with political and scientific guidance of the informal mining sector, restrictions on Hg availability and on sales from industrialized countries, and economic incentives for gold recovered using environmentally friendly methods instead of the present worst case example.

Acknowledgements

5 References

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