1. Introduction and background

Approximately 30 million individuals spread over virtually all developing countries are involved in extracting over 30 different minerals using rudimentary techniques (Veiga and Baker, 2004). Gold is the predominant product being worked since the price of the metal has increased three fold over the past 10 years. Its extraction on a small scale, however, induces extremely high levels of river siltation, mercury pollution, and many other environmental and social problems (Velasquez-Lopez et al., 2010).

In 2004, annual gold production from Artisanal Gold Mining (AGM) was estimated at 20–30% (500–800 tonnes) of total global production (Swain et al., 2007). A more recent study (Seccatore, 2012) placed production from AGM at about 392 tonnes/a or 12.2% of total output (2828 from organized mines (WGC, 2013) + 392 tonnes from AGM = 3220 tonnes).
Annual mercury releases to the environment from AGM operations based on UNEP (2013) and Swain et al. (2007) is 1400 tonnes and 1000 tonnes, respectively giving a global range of average ratio of tonnes of Hg
gwasted to tonnes of Auproduced between 2.5 and 3.5. Recently, Koekkoek (2013) projected the annual amount
of mercury released by AGM in 70 countries to be 1608 tonnes. This estimate represents 93% of the countries that use mercury in AGM.

The environmental and health impacts of mercury pollution from AGM have been well-documented in different parts of the world (Pfeiffer et al., 1989; Malm et al., 1990, 1995; Ikingura and Akagi, 1996; Veiga, 1997; Lacerda, 1997; Olivero and Solano, 1998; Malm, 1998; Harada et al., 1999; Akagi et al., 2000; Drake et al., 2001; Wasserman et al., 2003; Eisler, 2004; Castilhos et al., 2006; Böse-O’Reilly et al., 2008; Cordy et al., 2011, 2013). It seems that the health effects of mercury vapour emissions in workers and families living in mining towns is much more evident and dramatic than the effects of methylmercury by fish ingestion in mining communities (van Straaten, 2000; Drasch et al., 2001; Ogola et al., 2002; Feng et al., 2006; WHO, 2013; Sieber and Brain, 2014). The main cause of environmental problems related to mercury releases is amalgamation of the whole ore (Spiegel and Veiga, 2010) whereas the main health problem is caused by inhalation of metallic mercury vapours when amalgams are thermally decomposed without using a condenser or filter (Veiga and Baker, 2004).

The objective of this paper is to provide a review of mercury use in AGM identifying perceptions from different stakeholders (governments, NGOs, academics and artisanal gold miners) around the world that may have created barriers to introducing Hg-free practices or to reduce mercury pollution from artisanal gold miners. The data and comments presented in this article are the result of over 35 years of practical experience of the authors in the field of mercury and artisanal mining.

2. Gold amalgamation: an overview

Amalgamation is one of the oldest gold extraction methods. When mercury is added to gold and silver ores, it forms an amalgam (or paste) following contact with these metals. Mercury amalgamates all metals except iron and platinum. The heavy mass of liquid mercury with the solid amalgam inside can be separated from other minerals through panning. The amalgam is then squeezed by hand in a piece of fabric to eliminate the excess liquid mercury not bound to gold. The resulting amalgam consisting of 40–50% mercury can be separated from the gold by decomposition using a propane or gasoline torch at temperatures around 460 °C. This process produces a gold doré containing about 2–5% residual mercury, depending on the effectiveness of the evaporation process (Veiga and Hinton, 2002). In some cases, such as those observed in some African countries, when amalgams are burned in low-temperature bonfires, the doré will contain as much as 20% mercury (Veiga et al., 2006).

Two methods are used by operators to extract gold with mercury:

1. amalgamation of a gravity concentrate;
2. amalgamation of the whole ore.

The first method dramatically reduces mercury releases (losses) to the environment since only a small amount of material (concentrate) is amalgamated. The second method is responsible for the largest losses of mercury to the environment (Veiga and Hinton, 2002).

Most operators have the wrong perception that amalgamation is very efficient at extracting gold and that no mercury is lost in the process. When a miner is asked how much mercury he or she lost in the amalgamation process, they virtually all answer, “almost nothing”. However, when they are asked how much mercury they buy every month, they reveal the real mercury losses, since they would not buy mercury if they did not need it (Veiga and Baker, 2004).

Amalgamation is not complicated, but gold must be liberated from the gangue for the process to be effective. Mercury combines with gold to form a wide range of compounds, from AuHg, to Au₈Hg (Taggart, 1945). When amalgamating a concentrate, mercury losses occur mainly because of “mercury sickening” and loss of coalescence (or “flouring”). “Sickening” is caused by mercury oxidation or impurities such as oil, grease, clay minerals, sulfates, and sulfides on the mercury surface while “flouring” is the dispersion of mercury into small drops caused by “sickening” or by mechanical forces such as grinding (Beard, 1987). It is believed by the miners in most AGM regions of the world that addition of “amalgamation-aiding reagents” avoids complete mercury sickening and flouring, therefore eliminating mercury losses. In many parts of the world, miners add lemon juice, brown sugar, caustic soda, quicklime, tooth paste, baking powder, guava leaves, urea, cyanide, urine, or detergent to reduce “flouring” (Veiga et al., 2006). There is no study proving that such reagents increase the capacity of mercury to hold together and avoid formation of droplets. Neither are there studies about how these reagents work, although some do appear to be effective. Alteration of mercury’s surface tension or adsorption of such reagents to act as a surfactant is a possible way of enhancing mercury coalescence.

An experiment conducted by Veiga et al. (2009) demonstrated to Ecuadorian miners that amalgamation extracted only 26% of the gold from a gravity concentrate, whereas cyanidation extracted more than 90%. The low efficiency of gold extraction was attributed to the oxidation of the mercury. Pantoja and Alvarez (2000) recommended using an electrolytic process to remove mercury oxidation layers and form sodium-amalgam, which is more efficient in gold amalgamation than mercury alone. Their results were impressive, showing an increase of recovery of around 60% (using regular mercury) to 92% (using “activated” mercury). Mercury is activated in an electrolytic process with a 10% NaCl solution. Metallic mercury is connected via a copper wire to the negative pole of a 12-V motorbike battery and a rod of graphite that can be obtained from an old radio battery connected to the positive pole for 15 min (Fig. 1). “Activated” mercury is much more coalescent than “sick” mercury. As mercury salts are soluble at high pH values (Meech et al., 1998) and sodium-amalgam forms sodium hydroxide in water, this is likely the mechanism by which the surface of metallic mercury is cleaned from oils and mercury oxide. This process is similar to the industrial process used to manufacture caustic soda. Actually, the use of “charged mercury”, as this process is popularly known, is recommended by the Nevada Prospectors Association (Ralph, 2013).

Whole ore amalgamation is the oldest technique, culminating in the greatest environmental damage in gold processing. Mercury is introduced into a sluice box directly, the ore pulp is allowed to flow over copper-plates or the mercury is poured into small ball mills prior to grinding. This latter technique results in the greatest Hg loss since mercury droplets are formed during grinding, and are then dragged into the tailings that end up in the environment or are sent for cyanide leaching and then to the environment.

There is a general perception in the public domain that the main source of mercury pollution from AGM is amalgam burning (Veiga and Hinton, 2002). Amalgams usually contain 40–50% Hg and 40–60% of gold and silver. Thus, the emission level from amalgam burning is restricted to the amount of gold produced. In contrast, amalgamation of the entire ore requires the addition of much more mercury. Based on mass balances of 15 artisanal mining plants, Cordy et al. (2011) demonstrated that mercury losses when the
whole ore is amalgamated in ball mills is 10–15 times higher than when amalgam is decomposed in open pans by heating. On the other hand, amalgam-burning likely triggers the main health problems.

Amalgamation of the whole ore is a result of ignorance and/or “tradition”. It is also a convenient manner for the owners of processing centres to quickly produce gold for their clients (the miners). The concept of processing centres began to spread around the world in the 1990s, with the idea that this would prevent dispersing mercury used by individual miners. These centres extract a fraction (30% or less) of the gold by rudimentary processes usually associated with amalgamation and they retain the tailings with its residual gold as payment from the miners to the processing plant owner. This gold is then leached by the processing plant using cyanide. Worldwide, these centres are proliferating at artisanal mining and processing sites since they provide operators with a means to quickly process their ores for free or for a nominal fee (Veiga et al., 2014).

A major environmental problem linked to processing centres results from the cyanidation of mercury-contaminated tailings (Guimaraes et al., 2011). Soluble mercury cyanide species are formed and released into the environment. How mercury cyanide complexes, such as Hg(CN)₂(aq), bioaccumulate in aquatic organisms is not well-studied, but one can presume that methylmercury formation is a possible step. At many sites where mercury-contaminated tailings are leached with cyanide, nearby fish contain high levels of mercury (McDaniels et al., 2010). Worldwide, virtually all tailings left at processing centres are leached with cyanide. In some cases, the process is conducted in percolation vats, as been witnessed in Brazil, China, Colombia, Ecuador, Mozambique, Nicaragua, Peru, Venezuela, Tanzania and Zimbabwe (Veiga et al., 2014).

Attention is needed to organize these centres so that they do not have a large impact on exposed populations. Contamination can be observed far from the mercury source as in the Tumbes River system where mercury released in Ecuador travels to Peru, hundreds of kilometres away (Adler-Miserendino, 2012) generating international tension.

3. Interventions to reduce mercury pollution in AGM

Many interventions have been made by governments, academics, NGOs, and international agencies to reduce mercury pollution. Without a clear definition of what the source of the problem is, interventions have tended to focus on small artisanal panners, or micro-miners – those producing 0.1–0.5 g of gold per day and releasing an equal amount of mercury to the environment. Micro-miners have neither the education nor the capital to work properly. Furthermore, they are not in any way tried to stop their activities for training or formalization (Spiegel and Veiga, 2010). In fact, the general public has the perception that all artisanal miners are those panning for gold in the river banks. There is a wide variety of miners that can be classified as “artisanal”, ranging from those processing 5000 tonnes of ore per day to those panning 20 kg of gravel per day. The solution for the small-panner using mercury is very complicated as they are dispersed in the field and are mining for gold as a seasonal or temporary activity due to a lack of employment in rural areas (Hentschel et al., 2002). It is difficult to convince miners to adopt a “cleaner” procedure since their panning activities are compatible with their low income and knowledge. As Hilson (2007) explains, there is a poor understanding of artisanal mining dynamics and so, international organizations try to implement inappropriate support schemes and interventions. Usually they are not sustainable.

International development agencies rarely dedicate the time to find out about the needs of the miners (Siegel and Veiga, 2010). This criticism was also put forward by Hilson (2005), who suggested that any intervention must first assess “the number of people operating in AGM regions, their origins and ethnic backgrounds, ages, and educational levels”. The main problem is that when assistance is unwanted, it is not sustainable. Sirolli (1999) shouts with passion when he says: “if people do not wish to be helped, leave them alone. This should be the first principle of aid.”.

Interventions to deal with the owners of the Processing Centres producing 0.5–3 kg of gold per day are badly needed, but are unfortunately rare. These individuals are the main polluters. They have power and are in a “privileged position” that takes advantage of the ignorance and low capital of miners. This is at the very core of the problem. Mercury emissions cannot be reduced if these individuals do not change their poor practices of amalgamation followed by cyanidation. A better division of labour and more equitable participation of the miners in the process are required (Veiga et al., 2014).

Table 1 identifies the steps needed to implement a technical intervention programme in an artisanal mining community. First, it is important to identify the community, how they are organized, what they lack and what can be used as links to solve the identified sources of problems. Being known and trusted before, during and after intervention is fundamental in order to have the proposed solutions adopted and implemented by the miners in a sustainable fashion. Considering that artisanal miners usually have little education, it is important to understand that knowledge transfer will be slow. The most important reason for an artisanal miner to change their way of working is to produce more gold. One must
explore this aspect when introducing cleaner procedures (i.e., extracting gold from their tailings). Trainers should always be available to assist miners; ideally, they should also have a similar cultural background to that of the miners.

The introduction of technical improvements must coincide with constant presence of trainers (McDaniels et al., 2010). In fact, maintaining a presence in the community, promoting dialogue and participation as a means of building trust are critical steps for any community development work.

Different approaches to intervening in mining communities are taken by different groups, governments, and organizations around the world to reduce mercury use, emissions and release. Some believe legislation is the key while others think that introducing new technologies are the best solution. Government representatives, academics, and NGOs have concentrated their efforts on solutions for mercury pollution based on political actions that can reduce the availability of mercury to artisanal miners. In 2011, the European Union introduced restricted control for countries exporting mercury through a treaty signed with UNEP (United Nations Environmental Programme). The US followed-up in 2013 with similar restrictions on mercury commercialization. The international price of mercury has increased sharply from US$ 4.93/kg in 2003 to US$ 55.2/kg in 2011 to US$ 103.7/kg in 2014 (Metal-Pages, 2014; USGS, 2009). Mercury at AGM sites sells at up to twice the international price. This was recently observed in the Department of Antioquia in Colombia. In September 2007, mercury in the gold fields of Antioquia was sold at US$ 35/kg and in December 2009 at US$ 50/kg (Veiga, 2010; García and Molina, 2011). In 2014, the price jumped to US$ 150/kg. In the Brazilian Amazon, the price of mercury at AGM sites is close to US$ 300/kg.

The restrictions on mercury access have yielded better results than legislation limiting its use, such as in Brazil and French Guiana. Sousa et al. (2011) analyzed 20 laws, decrees, and resolutions in Brazil related to the use of mercury in AGM and concluded that these pieces of legislation “are stringent on paper and weak in their application and enforcement”. In 141 artisanal mining sites visited from 2006 to 2008 in the Brazilian Amazon, only one had an environmental license and mining permit to operate. French Guiana banned mercury in AGM in 2006 but despite the law, mercury is still in wide use, as reported in the literature and observed in the field (Veiga and Baker, 2004; Hammond et al., 2007; Telmer and Veiga, 2008; Howard et al., 2011). Similar to Brazil and Indonesia, the governments of Philippines (Valencia, 2013), Guyana (Dillard, 2012; Guyana Chronicles, 2013) and Colombia (Guiza-Suárez and Aristizabal, 2013) established or are establishing laws to prohibit or limit mercury use in AGM. Without any type of enforcement, these laws are a waste of valuable time and money that could be used to educate miners about cleaner procedures.

An agreement involving governments from 92 countries was signed in October 2013. The Minamata Convention on Mercury intends to limit mercury trading, in particular in developing countries (Selin, 2013). The implications of this inter-government agreement in artisanal mining communities are concerning, since without training and enforcement, artisanal miners will not change their polluting techniques.

The artisanal miners have long resisted changing their practices, based on belief that any modification will lead to a reduction in their gold production (Hinton et al., 2003). Many interventions in AGM have been delivered by those with no experience in the field. Recently, many “wannabe” experts have appeared with “magic” solutions aimed at eliminating mercury from AGM. Some of these solutions are usually poor adaptations of the methods used in large-scale mining. Hillson (2006) mentioned that many interventions “failed to identify appropriate mitigation measures, and has done little to advance understanding of why contamination persists”. There is no generic solution. An intervention must be appropriate for a specific ore, a specific site, and in accordance to the specific knowledge level of the artisanal miners. As a result, these “wannabes” tarnish the reputation of those trying to work seriously and so, artisanal miners lose trust in any solution coming from foreigners.

Veiga et al. (1995) discussed the inefficiency of the armed, the legal, the health, and the ecological approaches to the problem and concluded that education of miners is the most powerful way to reduce mercury pollution. This in fact was demonstrated by the UN Global Mercury Project where over 30,000 miners in six pilot countries were educated to adopt more efficient methods to recover gold and generating less pollution (McDaniels et al., 2010). Recently, Veiga (2014) reported findings from a small project financed by the US Department of State that led to the implementation of a demonstration gold processing plant in Ecuador to train more than 600 artisanal miners and community members from Peru, Ecuador, Colombia and Bolivia. The project led to the construction of more than 40 improved plants. The reduction of mercury releases and emissions were substantial, reaching 40% in Portovelo, Ecuador, 50% in Piura, Peru, and up to 60% in Segovia, Colombia.

4. Micro-credit

Technological education is not always sufficient to induce significant change in artisanal miners’ techniques. Capital is needed as well. When a relatively costly technology is considered, the idea of offering micro-credits to miners is often suggested. Micro-credits do not make any difference in the modernization of artisanal miners. They need a capital influx of about US$ 10,000 per tonne of ore being processed per day to establish a cleaner and profitable processing facility (plus improvements in mining as well). This is the main challenge here since banks and governments are not prepared to create lines of credits for these individuals. Artisanal miners usually do not measure geological gold reserves. They establish their production plan based on the day-by-day results. This is unacceptable to a bank. Even if the miners show a
minimum reserve that could guarantee the loan, banks are still suspicious. This issue was thoroughly studied under the UNIDO Global Mercury Project in 2006–2008 (McDaniels et al., 2010). It is clear that without formalization, miners will not be able to access the most basic forms of micro-credit, but formalization is a process, not a product. Even the most elaborate policies to formalize mining activities will fail if a government lacks the will to implement a plan; if miners perceive licensing as a threat; or if miners cannot afford the cost to join the legal economy (Siegel and Veiga, 2009).

Hilson (2011) confirmed that the examples of microcredit projects in African AGM sites were not successful. This is because, for many reasons, artisanal miners are not fully legalized and secondly, banks are very selective about which clients deserve the loan and demand collateral. Knowledge about the geological reserves, businesses plans, and other requests that would be more appropriate to organized large gold companies, is expected of artisanal miners.

Worldwide, not a single artisanal mine site is known that has evolved into a responsible small-mining operation thanks to bank financing. Usually, the investors are private local capitalists. This has been observed in Portovelo, Ecuador where about 40 good small-scale plants processing 60–300 tonnes of ore/day are currently in operation because of private investors.

5. Formalization of artisanal miners

There is a dominant perception from the governments of countries impacted by AGM that mercury pollution can be controlled through formalization of the artisanal miners. The formalization approach has been tried by the majority of federal governments of developing countries that face problems with informal or illegal1 artisanal mining. Chen (2007) suggests that informal employment comprises 50–75% of non-agricultural employment in developing countries. When the agricultural sector is considered to be an informal activity, the proportion of informal employment can be 93% of the total employment, as in India, for example. Why, then, are governments so interested in formalizing informal miners and not other sectors of the economy? The answer is simple: the opportunity to tax. However, an artisanal miner, micro, small, medium, or large in size, will not pay a dollar to be formalized or to adopt a new cleaner procedure if they do not see two dollars as a result (Hinton et al., 2003). Unfortunately, governments usually do not have the technical capacity to deal with unregulated artisanal miners. The absence of government authorities in remote artisanal mining areas is a major part of the problem (Hilson and Vieira, 2007). Without training and education, miners do not know how to obtain legal mineral titles (McDaniels et al., 2010) or how to improve their gold extraction methods.

Good examples of successful formalization are rare. While the approach has relative merit in dealing with small, medium and large artisanal mining operations, it cannot work with micro-miners–those millions of miners who pan the river banks to produce 0.1–0.5 g of gold per day. This activity is usually driven by poverty and subsistence. Organized companies can be required to implement cleaner production methods and follow the laws. However, it is rare to see governments enforcing the laws and providing technical advice on how to apply cleaner techniques (MMSD, 2002; Song and Mu, 2012).

In theory, the formalization of artisanal miners is a step towards cleaner production since this creates a sense of ownership of the mineral title giving transferable capital to the miners (Siegel and Veiga, 2009). In a practical sense, formalization is an intricate process for artisanal miners. Not all miners can fulfill the legal requirements for formalization. It is important to note that, in most countries, formalization by the Ministry of Mines does not imply that a legal condition is satisfied since environmental permits must also be obtained from the Ministry of Environment (Sousa et al., 2011).

The numbers of formalized miners are usually too small to make a significant difference in the disorganization and pollution observed at artisanal mining sites. For example, after three years of promotion and planning, the formalization of 450,000 Peruvian artisanal miners proved to be a fiasco due to the bureaucratic procedures in the formalization process. Peruvian authorities recognized that out of the 50,000 miners who applied to obtain a formal mineral title, only 27,000 would be formalized in the short to medium term (Expreso Peru, 2012). A similar failure to formalize artisanal miners is described by Guiza-Suárez and Aristizábal (2013) in Colombia, where 87% of all mining operations are illegal. Between 1993 and 2008, after government efforts to formalize the mines, of 3631 applications, only 23 mines were legalized – less than 1%.

Despite all legal restrictions, artisanal mining will occur, particularly in areas where law enforcement is nonexistent. Enforcement is not a simple matter since the majority of the artisanal operations are located in remote areas (Hilson, 2002).

The formalization process is linked to another major hurdle: awkward legislation related to artisanal mining. Artisanal mining refers to a rudimentary type of mining and processing used to process gold and other minerals, whereas small mining refers only to the size of the operation (Veiga, 1997). A small mine may operate in a conventional or artisanal fashion. Alternatively, an artisanal mining operation can process over 10,000 tonnes of ore per day, which should not be considered “small” (Table 2). The main attribute of conventional and artisanal activities lies in the technologies applied (Table 3).

Few countries have clear regulations or definitions of artisanal mining, but almost all relate the term to the size of the operation. In Peru, Law 27651 of 1992 (Peru, 1992) provides definitions based on production capacity. Here, a large mine is one that exploits and processes more than 5000 tonnes of ore per day (tpd) while a medium mine processes from 150 to 5000 tpd. The Ecuadorian Mining Law of Jan 29, 2009, defines three types of mining: Artisanal, Small, and Large-scale (Vergara, 2009). According to Ch.

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1 Illegal mining is identified herein when the activity is conducted without a proper title, authorization, or concession issued by the competent authorities, while informal mining is a set of deficiencies in environmental management, technical assistance and development, access to information and acceptable working conditions (Hentschel et al., 2002).

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<th>Type of Mining</th>
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<th>Legal situation</th>
<th>Mechanization</th>
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<td>Artisanal (rudimentary)</td>
<td>Micro</td>
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<td>Small</td>
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<td>Semi-mechanized</td>
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<td>Conventional</td>
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<th>Attributes of artisanal and conventional mining operations.</th>
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<tr>
<td>Conventional</td>
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<td>Geology, drilling</td>
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<td>Reserves</td>
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<td>Feasibility study</td>
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2. Art. 138 of this law, a small-scale mine has a capacity to exploit and process up to 300 tonnes of ore per day. Everything above this capacity is considered large-scale and subject to high taxes. Artisanal miners are individuals, families, or cooperatives that mine for subsistence (Delgado, 2009).

The lack of distinction between small-scale conventional mining and artisanal mining is usually the source of formalization problems. In addition, formalization cannot be implemented and enforced at sites where artisanal miners are not organized. Education is the first step towards formalization; otherwise, governments can only formalize pollution since artisanal miners will not change their way of operating.

6. Gold concentration to reduce mercury pollution

The main means for reducing mercury emissions is to introduce gold concentration methods. Concentration by gravity or flotation can also offer the benefit of recovering additional values such as copper minerals. This is exactly what the artisanal miners in Portovelo, Ecuador are doing. Capital and technology are helping artisanal miners to become more organized small-miners who now produce more gold. More than 40 plants in Portovelo and 39 plants in Antioquia, Colombia (Veiga, 2014) are concentrating gold and copper minerals by gravity separation and flotation and eventually leaching only the pyrite (gold-bearing sulphide) concentrate with cyanide, thus reducing the amount of material to be leached. Old tailings are also being reprocessed. This approach, together with the presence of local capitalists, have substantially reduced mercury pollution, since copper concentrate with gold, are sold directly to smelters.

Even the best concentrator in the world will not work if the operators do not have proper knowledge of how the gold is associated with other minerals in the ore as well as how fine the gold is. A typical size distribution of gold in tailings from a quartz vein artisanal mining operation is shown in Fig. 2. Fine gold particles are associated with the coarse fractions, usually unliberated from the silicate gangue, while in the fine fractions, fine gold is not trapped (or recovered) by the rudimentary concentration methods. The problem with concentration of fine particles can be resolved by using centrifuges, flotation, or even cyanidation. The liberation problem must be solved with changes in the grinding and classification (screens or cyclones), which are the most expensive steps in gold processing.

Most gravity concentration methods used in artisanal mining are not continuous (i.e., they must be stopped to discharge the concentrate). Miners working with alluvial ores control their activities based on how “yellow is the concentrate”. This is a very common mistake. High gold grade in concentrates do not reflect high gold recoveries. Usually, the relationship is the opposite. Fig. 3 shows a hypothetical graph that exemplifies the antagonistic behaviour of gold recovery and concentrate grade. A large mass of concentrate implies that the gold grade is low but the recovery is high and vice versa. The choice of an operating point on this curve (where a concentrate from a sluice box or centrifuge is to be discharged) is an economic decision.

Introducing concentration principles to artisanal miners is not easy since many miners believe that concentration is a waste of time and gold will be lost. In fact, this is true when gold is extremely fine but in the majority of cases, problems occur because of poor grinding, classification, and concentration operations. This is the rationale behind amalgamation of the whole ore; it is cheap and the miners immediately see gold in their hands. It is important to show that in a well-developed concentration process, reducing the mass of the material (e.g., to less than 10% of its original mass, will lower by a large extent the cost of leaching and/or amalgamation of the concentrate). At the end of the process – a well-conducted one – there will be more money generated when concentrating the ore. As a positive side-effect, less mercury or cyanide will be used. Although this is routine for mining engineers working in large companies, it is a challenge to introduce these concepts to AGM workers, because of the lack of education in the sector.

There is also a perception that gold concentration equipment is expensive. Even a home-made wood zigzag sluice box can be very efficient with insignificant cost (Veiga et al., 2006). A small centrifuge, the most efficient gold gravity concentrator, is also affordable and can pay back the investment very quickly. Flotation has been widely used in AGM operations in Brazil, Ecuador, Colombia and Chile and there are many options in the market of inexpensive flotation cells.

Concentration requires previous liberation of the gold particles. Liberation of the mineral of interest (gold) from the gangue by grinding is not part of the vocabulary of artisanal miners. This idea is probably inherited from alluvial operations, where in most cases (but not always), gold is naturally liberated by abrasion in the water stream. Working with secondary gold deposits (alluvial, colluvial and eluvial), most miners believe that gold is always free. However, for secondary deposits, gold particles are either partially liberated or completely trapped within gangue minerals (Spiegel and Veiga, 2010). The gold recoveries are very low as it is rare to see any AGM grinding these types of ores. Ball mill grinding is the most efficient but also the most expensive step to liberate gold. It requires high energy and high investment. However, even a Chilean mill (also known as Muller pan), as observed in many Andean countries (Velazquez-Lopez et al., 2010) or a hammer mill can be an inexpensive and relatively efficient solution to liberate gold before concentration, if well operated.

Unlike other minerals, gold does not need to be completely free to be concentrated by gravity methods. Gold associated with quartz particles can increase the weight of a particle that reports to the concentrate. Unliberated gold can be leached with cyanide if the gold particle is exposed but cannot be trapped by mercury and

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**Fig. 2.** Typical Au grade distribution of artisanal mining tailings.

**Fig. 3.** Hypothetical relationship between mass of concentrate, gold grade and gold recovery.
so is lost to the amalgamation tailings. However, when the ore is concentrated, the particles can then be reground (and the gold liberated) at a relatively low cost.

When grinding ores, artisanal miners rarely use classification (screens or cyclones) which can improve grinding efficiency. It is common to find miners believing that a circulating load in a ball mill is a bad practice. They believe that returning between 100 and 400% of the material to the ball mill feed is a waste of equipment. However, a high circulating load can maximize output rates at a narrower range of product size (Mular et al., 2002) and thus, a higher degree of liberation is generated.

7. Treatment of gravity concentrates

Once a concentrate is obtained, there are many methods to extract gold from it. The mining companies usually extract the relatively coarse gold by gravity separation. The gravity concentrate is then, re-concentrated in a shaking table to obtain a very rich concentrate to be directly smelted with a flux such as borax. All tailings are either floated and/or leached with cyanide.

7.1. Borax

The use of borax (Na2B4O7·10H2O) as a flux to melt gold concentrates is a very old technique to reduce the melting point of the mixture of minerals, bringing the silicate and oxide impurities to the slag. The use of borax alone has been publicized recently as a way to replace amalgamation of gravity concentrates (Amankwah et al., 2010). This borax method is only efficient with very low sulphide content concentrates and in materials that are not ground too fine (Appel and Na-Oy, 2013). The technique emphasizes the use of borax to lower the melting point of the minerals (impurities in the concentrate) to about 1064 °C, which is the gold melting point and a temperature reachable using charcoal and a blower, or a butane/propane torch (Appel and Na-Oy, 2011). Their studies indicate that for the process to be effective, the concentration process must achieve high gold grades (>30,000 ppm Au or 3% Au). As explained in Fig. 3, there is a balance between grade and recovery. The higher the concentrate grade, the lower the gold recovery. Enrichment to a 3% Au concentrate grade is much too high and will compromise gold recovery to an unacceptable level.

A site-specific investigation was conducted with a sulphide ore from Portovelo, Ecuador (Angeloci-Santos, 2013). A sample of centrifuge-sluice box concentrate with 3330 ppm of gold and 1170 ppm silver was used. Using 50 g of concentrate to be melted with 50 g of borax the amounts of gold and silver were low: 0.165 g and 0.06 g respectively. Several tests of direct smelting with borax were conducted with no to little success. This series of tests, following the method described by Appel and Na-Oy (2011), was unsuccessful because there was no separation of the gold and slag due to the high amount of sulphides in the concentrate sample. In all tests, it was clear that the mass of gold was really too small to carry all gold particles to the bottom of the crucible. The only successful test involved adding a mixture of KNO3, SiO2 and NaHCO3 to oxidize sulphides and reduce slag viscosity. A recipe of a mixture of fluxes in the following proportion: 1:1:0.25:0.25 concentrate:borax:KNO3:SiO2:NaHCO3 was used. Formation of a well-defined interface between slag and gold bead was noticed while the slag was more vitreous, indicating that a higher amount of metal was separated. Around 84% of the gold was recovered; the rest was lost in the slag. In fact, the assay of slag showed a high grade of gold (840 ppm) and the gold bead contained 69.35 ppm Au that still needed further treatment.

It is important to note that gold recovery must also account for losses in the concentration step as well. In the case of the Ecuadorian concentrate tested, the gold recovery was around 70% for the centrifuge and 70% for the sluice box (to increase the gold grade to 3330 ppm). In the best case scenario (84% of gold recovery in the smelting process), the global recovery would be about 41%. Comparing direct smelting to the current amalgamation method, the gold recovery might be slightly better with direct smelting, but impractical and costly (energy-wise) to be conducted on 175 kg of concentrate per day. In addition, the slag must be recycled back for cyanidation.

The process seems useful for a narrow range of artisanal miners and types of ores (e.g. those without sulphides). It may be useful for micro-miners producing very small amounts of gold per day and working with alluvial ores in water streams. But they must have resources to melt gold and access to the flux.

7.2. Cyanide

Almost all industrial gold mining companies no longer use amalgamation to extract gold. Instead, they carry out cyanidation of the whole ore (when gold is very fine) or concentration (gravity and/or flotation) followed by cyanidation of the concentrate.

The public thinking about cyanide is the main hurdle to accept gold cyanidation as a technique cleaner than amalgamation. The general perception is that cyanide is much more toxic than mercury, as the acute effects of cyanide are much more dramatic than mercury (which is an accumulated chronic threat over time). Most cyanide complexes can be decomposed to less toxic species (ammonia and carbon dioxide). This cannot happen with mercury species. The neurological chronic effects of mercury and its compounds are many times more serious than the chronic effects of cyanide-derived compounds (Veiga and Baker, 2004).

Public perception about cyanide has its roots in judicial executions, suicidal acts, or death by ingestion of cyanogenic plants. Bitter cassava can contain up to 400 mg/kg and it is not rare to hear of fatal incidents with inadvertent consumption (Akontowa and Tunwashe, 1992; Kwok, 2008).

In Guyana, two incidents made cyanide an even greater villain. The first was the mass suicide in 1978 of 909 members of a religious cult conducted using a solution of cyanide in Kool-Aid. The second incident occurred in 1995 when 1.25 million cubic metres of gold mine tailings from the Canadian company Omai Gold Mine spilled into the Essequibo River (Davidson, 1995). As a consequence, the Guyanese Government banned cyanide use in gold mines. However, mercury is freely used by artisanal miners. The Government of Costa Rica recently banned cyanide in gold mining (Friends of the Earth, 2010), however, artisanal miners still use mercury to extract gold.

Nowadays, all conventional gold mines destroy cyanide by oxidation and follow regulations to achieve release levels less than 1 mg/L of total cyanide (MMER, 2002). In contrast, processing centres at artisanal mine sites rarely destroy cyanide (Velasquez-Lopez et al., 2011).

One of the limitations to the wider use of cyanide replacing amalgamation of concentrates is the slow rate of coarse gold dissolution which is controlled by the slow dissolved oxygen content in the leach solution (Marsden and House, 2006). Some companies have developed pieces of equipment for gold extraction using intensive cyanidation. Veiga et al. (2009) proposed an intensive cyanidation method for small-miners using a simplified methodology that does not require expensive equipment. The methodology suggests that the concentrate generated by a small-scale plant could be intensively leached by cyanide, by adding an oxidizing agent such as H2O2 or Vanish® or Oxiclean® which has around 16–21% of H2O2 in 50–66% of sodium percarbonate (Bracken and Tietz, 2005) in a small ball mill (the same used for whole ore amalgamation) with a sturdy, perforated, plastic capsule filled with activated charcoal inside a nylon screen. The
concentration of H$_2$O$_2$ and NaCN are usually 0.3 g/L and 20 g/L, respectively. The amount of activated carbon is equal to 60 g per gram of Au contained in the concentrate feed.

Sousa et al. (2010) achieved a gold extraction of 95% in 24 h using the method described above in an AGM operation in Brazil to recover gold from old tailings previously concentrated at lower recovery with a centrifuge. This process was also successfully demonstrated to miners in Ecuador and Colombia (Angeloci-Santos, 2013). This process can, therefore, be easily adapted by processing centres and even artisanal miners. The capital cost comprises acquisition of an efficient gravity concentrator (e.g. centrifuge) and a small-ball mill already in use by many processors.

7.3. Alternative lixiviants

Researchers have been calling for the use of thiourea (Eisele et al., 1988) or thiosulphate (Rath et al., 2003) to leach gold for some time. Despite being less toxic and environmentally safer than mercury and cyanide, the reagents are not generally available in remote regions and the leaching process requires strict control of parameters such as pH and Eh which are complicated for unskilled miners. Many manufacturers also offer different alternatives to mercury and cyanide as a “green” gold-leaching agent. Commercial products are available as a “panacea” for mercury pollution. Their compositions are rarely disclosed so it is difficult to investigate their real efficiencies and impacts. In addition, it seems that the strategy of these companies is to keep the miners as their perpetual clients using their proprietary reagents.

Chlorine leaching has been studied as a replacement for both mercury and cyanide processing. This method was applied extensively in the 1800s with cyanidation replacing it in the 1890s because of effectiveness and safety concerns. These early procedures were conducted in wooden tanks by pumping chlorine gas through the ore inside a covered vat for 12–18 h (Eissler, 1888). The main problem faced by the engineers in the 1800s was the difficulty in conducting the leach process in agitated steel tanks because of corrosion.

MINTEK, a South African research centre, has developed a method to extract gold from gravity concentrates based on chlorine leaching. The iGoli gold extraction system is intended for artisanal use as a substitute for amalgamation. A small (30 L) agitated leach tank is used to which a 1:1 mixture of HCl @ 33% and bleach (sodium hypochlorite @ 16%) is added. After the gold is recovered, calcium chloride, sodium hydroxide, andapatite are added to the effluent to precipitate the other metals in solution to an inert form. Recoveries as high as 98% were achieved by Mahlatsi and Guest (2003). On the other hand, the process is chemically complicated and technical knowledge is crucial to solve extraction problems that might appear using different ore concentrations. There is also no recovery of silver in this system, since chlorination of this metal generates an insoluble compound (AgCl). Storage of sodium hypochlorite also brings additional problems as this solution is not stable in hot climates.

An electro-chlorination or electro-leaching process has been proposed by Barbosa et al. (2002) as a potential candidate to substitute cyanide and amalgamation in AGM. The idea is to: a) produce chlorine from sodium chloride solution; b) oxidize sulphides that trap the gold c) leach the gold in an agitated pulp; and d) plate it on the cathode. Angeloci-Santos (2013) conducted about 30 tests of electro-leaching at pH 1.5, using 30 g/L of NaCl and 1 g/L of NaBr to leach an Ecuadorian centrifuge concentrate containing 1118 ppm of gold. Due to the high grade of copper and iron sulphide minerals in the concentrate, gold extraction, even for 24 h, was very low (<10%). Greaves et al. (1990) investigated chlorine as a substitute for cyanide on several different types of gold ores. Their recoveries in high-sulphide ores were 10.2% for a 35% sulphide content ore and 6.4% for a 20% sulphide content ore. When pre-oxidized, these values increased to 20.4 and 70%, respectively. Chlorination seems to be complicated for unskilled miners and applicable only in the case of simple gold ores (i.e. low sulphides content).

In all cases of alternative lixiviants, the core of the problem is obtaining a gold concentrate to be leached. This is critical, as it reduces substantially the mass of material in the gold leaching process with any type of reagent.

7.4. Retorts

A large majority of artisanal miners separate mercury from gold in amalgam by heating in an open pan. They do not use methods to condense mercury such as “retorts” because they do not believe that mercury vapours are harmful. However, few people in AGM sites have clear knowledge about the relative toxicity of metallic mercury. Veiga et al. (1995) described an episode in 1987 where environmentalists were trapped in a theatrical performance when an artisanal mining leader ingested metallic mercury in front of TV cameras to show that the mercury used in gold mining is inoffensive. The truth of the matter is that when metallic mercury is ingested, the body can excrete most of it within about 30 days. This is completely different from methylmercury ingested with contaminated fish. Over long time periods, metallic mercury can result in a health problem but this derives from breathing mercury vapour.

The assessment study by Jonsson et al. (2009) investigated use of a water-pipe steel retort (Veiga et al., 1995) with miners for five months and solved the problems they faced when using the equipment. The authors stressed that miners usually stop using retorts when they face any kind of problem. Veiga et al. (2006) have given several reasons why miners do not adopt retorts sustainably (Table 4). The main argument encountered is the lack of being able to inspect the burning process. Hilson and Pardie (2006) described the UNIDO project in Ghana which introduced a glass retort to make the mercury distillation process more visible. With a cost of US$ 520, low capacity, highly breakable, and unavailable spare parts, this initiative was unsuccessful. This was eventually solved by

<table>
<thead>
<tr>
<th>Arguments</th>
<th>Reasons</th>
</tr>
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<tbody>
<tr>
<td>Mercury is inexpensive</td>
<td>Miners do not see immediate health issues when exposed to Hg vapours</td>
</tr>
<tr>
<td>Retorts are expensive</td>
<td>Miners do not know inexpensive options</td>
</tr>
<tr>
<td>It takes time (sometimes miners are vulnerable to bandits)</td>
<td>Retorting temperature is too low</td>
</tr>
<tr>
<td>Inexperience in operating a retort</td>
<td>Lack of assistance in operation</td>
</tr>
<tr>
<td>Gold is lost during retorting</td>
<td>With iron retorts, the amalgam is not visible so miners believe it has been lost</td>
</tr>
<tr>
<td>Gold sticks to the retort crucible</td>
<td>Occurs when the temperature is too high or when crucible is not lined with a thin layer of clay, talc or soot</td>
</tr>
<tr>
<td>Recovered mercury loses coalescence</td>
<td>Sometimes condensed Hg disperses into fine droplets</td>
</tr>
<tr>
<td>Gold comes out brown from steel retorts</td>
<td>Cause is unknown; it is probably due to a superficial reaction with iron</td>
</tr>
</tbody>
</table>
Veiga et al. (2006) using cheap and easily accessible salad bowl retorts (Fig. 4). A large bowl of stainless or enamelled steel, found in any kitchen store, is perforated to accommodate a small bowl to hold the amalgam. The set is covered with a glass bowl and sealed with wet sand. This allows the miners to follow the amalgam burning process and witness when the process is complete. This unit has been successfully introduced into over 20 countries. The main drawback is that the glass cover cools slowly and miners do not want to wait to have the gold doré in their hands. In this case after some initial experiments with the glass cover, an enamelled steel cover can be used which can be quickly cooled with water.

Another perception that creates resistance to retorts is that it takes too much time to eliminate mercury from the amalgam. Retort crucibles can be made with thinner steel walls that take less time to heat up. As many miners burn amalgams in bonfires, a manual air-blower bellows can also be built using a piece of pipe and a plastic bag to blow air into the fire to improve heat generation. The “mvuto” used by operators in Zimbabwe is a plastic bag attached to a steel pipe that blows into a bonfire. The increased temperature reduced the amalgam burning time from 30 to 15 min (Veiga et al., 2006) (Fig. 5).

8. Conclusion

The perceptions of artisanal miners, governments, academics, NGOs, and the general public must be dealt with using the same rigour as the facts. It is important to understand the needs of the miners, the source of their perceptions, and the knowledge to engage them in friendly discussions.

Legislations are not always a solution for the mercury problem. Hilson and Vieira (2007) stated that “government officers must be convinced that policy and legislative variations are deterring environmental management efforts in the region”. Complex legislation creates a jungle of bureaucracy that is pushing the miners even farther away from formalization. In addition, formalization without enforcement is just formalizing more pollution.

Many perceptions are also created internationally by different sectors interested in selling equipment, consulting or “magic solutions” to artisanal miners. There are many methods available to reduce and eliminate mercury in artisanal gold mining, but the most important one is to amalgamate a gold concentrate, not the whole ore. Extraction of gold from a small mass of concentrate with intensive cyanidation is the most realistic process that does not require high investment and extensive knowledge since artisanal miners are already familiar with using cyanide (Veiga et al., 2009).

Any method to replace mercury should first address the needs and beliefs of the miners. It is important to bring technological options to miners. They must be comfortable in selecting what is right for them. Financial assistance and education can help avoid the need for “quick money” from amalgamation. The mercury-cyanide contamination generated by the processing centres is a far more complex problem with significant social roots. A deeper investigation and intervention in processing centres is needed to organize the business to operate in a less-environmentally harmful and more equitable way.

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References


Fig. 4. Kitchen-bowls retort in Colombia.

Fig. 5. AGM in Zimbabwe using improvised bellows to increase the temperature of the fire during amalgam retorting. Photo: S. Metcalf.

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