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Abandoned Artisanal Gold Mines in the Brazilian Amazon: A Legacy of Mercury Pollution

Marcello M. Veiga and Jennifer J. Hinton

Abstract

The modern gold rush in the Brazilian Amazon attracted millions of people to become artisanal miners in order to escape complete social marginalization. The rudimentary nature of artisanal mining activities often generates a legacy of extensive environmental degradation, both during operations and well after mining activities have ceased. One of the most significant environmental impacts is derived from the use of mercury (Hg), which is illegal for use in gold amalgamation in Brazil, but continues to be the preferred method employed by artisanal gold miners. The general population is unaware of the capricious nature of mercury and artisanal mining activities. Moreover, individuals in positions of political or economic influence tend to be negatively biased towards artisanal mining and government policies do not effectively address the realities of these activities. Affected communities have consequently been ignored, and mistrust towards outside parties is high. Not surprisingly, miners are suspicious of and unlikely to employ externally derived solutions to reduce mercury emissions. This article reviews the use of mercury in artisanal mining and highlights the role miners, governments and non-governmental organizations (NGOs) have played in communicating facts, perpetuating myths and deriving solutions for mercury pollution. This article also raises some key concerns that must be addressed to understand the behaviour of mercury in the environment and identifies solutions for problems facing communities where artisanal gold mining operations have been abandoned.

Keywords: Mercury pollution; artisanal gold mining; abandoned mines; public perception, artisanal mining regulation.

1. Introduction

1.1 Artisanal miners everywhere

Most established mining companies have implemented policies and protocols to satisfy increasingly stringent regulatory requirements and public pressure, however, large numbers of people around the world rely on largely unregulated artisanal mining for subsistence.

In 1993, it was estimated that about 6 million of the world's 30 million mine workers were engaged in artisanal mining in more than 40 countries, extracting over 30 different types of mineral substances (Noetstaller, 1995). The International Labour Organization (ILO) estimates that the number of artisanal miners is currently around 13 million (Table 1) in 55 countries and rising, which suggests that 80 to 100 million people worldwide are directly and indirectly dependent on this activity for their livelihood (ILO, 1999). As gold is easily sold and not influenced by the instability of local governments, it is by far the most important mineral extracted by artisanal miners. Artisanal miners have been extracting gold in virtually all Latin American countries, but most mining activities take place in the Brazilian Amazon region. In 1995, it was estimated that as many as one million artisanal miners were extracting gold in Latin America, with production as high as 200 tonnes (6.4 million oz), with the largest contingent of miners (200,000 to 400,000) working in Brazil extracting 30 to 50 tonnes (Veiga, 1997).

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Table 1. Employment in artisanal mining

Continent	Number of miners (million)
Asia/Pacific	6.7 - 7.2
Africa	3.0 - 3.7
Latin America	1.4 - 1.6
Developed countries	0.4 - 0.7
Total	11.5 - 13.2

Source: ILO (1999)

The artisanal mining cycle is well known: discovery, migration, and relative economic prosperity are followed by resource depletion, outmigration and economic destitution. Drugs, prostitution, disease, gambling, alcohol abuse, and degradation of moral standards are frequent consequences of the chaotic occupation at mining sites. It is apparent that the economic benefits obtained by the miners do not compensate for the deplorable socio-economic conditions left to surrounding communities. After depletion of easily exploitable gold reserves, sites are abandoned, and those who remain contend with a legacy of environmental devastation and extreme poverty. These people have little opportunity to escape their circumstances. Thousands of abandoned artisanal mines can be found in Latin America, particularly in the Brazilian Amazon region, and those currently operating will undoubtedly experience the same fate. This article focuses on an important consequence of the abandonment of artisanal mines: mercury pollution. By better understanding the causes and consequences of mine abandonment, effective measures for prevention and mitigation of mercury pollution are more likely to be developed and implemented.

1.2. Artisanal mining defined

Frequently, the terms artisanal, small-scale and peasant miners are applied to low-tech manual panners, although this activity actually ranges from individual panning to large dredging operations. However, even in large-scale operations with highly mechanised extraction techniques, artisanal miners do not conduct the same kind of mine planning as organised mining companies, but employ methods that make the most money in the shortest period of time. The term artisanal mining seems to best encompass all definitions and designations, as it includes all small, medium, large, informal, legal and illegal miners who use rudimentary processes to extract gold from secondary and primary ore bodies.

The Portuguese labeled artisanal miners *grimpeiros* and Brazilians have adapted the name to *garimpeiros*. Later on, this term was improperly applied to those individual panners, who for three centuries tried to make their fortune or merely survive from the river gravel or surface gold ores.

Table 2. Characteristics of conventional versus artisanal mining

Conventional mining	Artisanal mining
Geology, drilling	Feeling, testing
Reserve characterisation	Subsistence
Engineering	Curiosity, intuition
Planning and feasibility	Extraction for short-term results
Sophisticated equipment	Rudimentary devices

The term *garimpeiro* is now formally included in the language to designate artisanal miners in general. *Garimpo* is the worksite or village and *garimpagem* is the mining activity conducted by *garimpeiros*. In Portuguese, these terms still have negative connotations associated with smuggling or clandestine activities.

In many countries, artisanal mining activities may also be defined on the basis of the scale of production (i.e. small-scale miners) or the type of ore exploited (e.g. placer miners). The Brazilian Law 7805, of 20 July 1989, states that only alluvial, colluvial and elluvial deposits are available to "organised *garimpeiros*", i.e. cooperatives or associations of artisanal miners (Barreto, 1993). Brazilian legislation actually excludes primary gold ore extraction from *garimpeiros*, although they were the discoverers of all major gold deposits currently being exploited by formal, established companies in the Amazon. Without technical support and investment, primary ores are generally inaccessible to artisanal miners, thus their activities are often 'naturally' controlled by the type of ore deposit.

Lawmakers usually do not consider the manner in which the work is carried out to be the most effective means for identification and characterisation of artisanal mining. Driven by survival and the need to support a family, artisanal miners employ instinct and intuition to identify and extract economic resources. Resources are simply not available to conduct 'classical' geological exploration, drilling, reserve characterisation, ore tonnage determination and engineering studies (Table 2). The artisanal miners have never learned the simple techniques needed to establish a minimum mineable reserve, which would enable them to plan safe operation and closure procedures, and their future. Ultimately, most artisanal miners are driven by survival, working instinctively to satisfy the needs of their family.

1.3 Gold rush in the Amazon

The contemporary gold rush in the Amazon was triggered in January 1980 when a solitary panner, José Feitosa, found gold in Serra Pelada. The mineral claim was already staked by a state-owned mining company, which had not investigated the presence of gold, but only iron and manganese. Serra Pelada is a historical landmark of a social phenomenon that is not likely to be repeated. At the

Plate 1. Serra Pelada in 1983 (Photo: Arthur Bernadelli)

Plate 2. Serra Pelada in 1997 (Photo: John Meech)

end of the 1970s, the Brazilian military government was seriously unpopular and the petroleum crisis was consuming the country's monetary reserves. When gold was discovered at Serra Pelada, the government intervened in the matter, creating the first artisanal mining reserve and encouraging people to move to the Amazon. About 80,000 men (Plate 1) from different parts of the world worked like ants in Serra Pelada to produce about 90 tonnes of gold from a single open pit (Feijão and Pinto, 1992). All technologies, from wooden sluice boxes to bioleaching, were used in Serra Pelada to extract gold.

At present, the open pit is flooded and less than 800 miners are struggling to survive by dredging sediments from the bottom (Plate 2) or reprocessing Hg-contaminated tailings. The former mining camp is now a shantytown with no basic infrastructure.

In 1989, more than one million gold miners were believed to be working at 2000 sites in the Brazilian Amazon producing an average of 100 tonnes of Au per annum (Feijão and Pinto, 1992). Today, less than 200,000 miners are struggling to produce 20 tonnes/year, which according to IBGM (2001), represents 30% of Brazil's gold

mining production. Government sources believe that the Brazilian *garimpos* (artisanal mining sites) have recently been producing only 10 tonnes of gold annually (Nery and Silva, 2000). With the exhaustion of the easily extractable ore, low gold prices and high fuel costs, it is safe to assume that most of the mining sites are currently being abandoned and that no effort is being made to rehabilitate pits or to contain tailings. The widespread misuse of mercury associated with these activities has consequently generated thousands of polluted sites with impacts extending far beyond localized ecological degradation.

1.4 Artisanal mining methods and mercury losses to the environment

Gold amalgamation using mercury is the preferred method employed by artisanal gold miners in the Amazon. When used correctly, mercury is an effective, simple and very inexpensive reagent to extract gold (1kg of Hg costs ~1g of Au). All attempts to eliminate mercury amalgamation by introducing alternative techniques, such as gravity separation, have been unsuccessful. In these cases, mercury use was reduced, but never eliminated completely. Cyanidation has been widely adopted by most organized mining companies but is rarely used by *garimpeiros* (Veiga, 1997). While it yields high levels of gold recovery, the cyanidation process requires much more skill and investment than simple amalgamation.

In Brazil, as in many Latin American countries, the use of mercury in mining is illegal. Mercury imports are only permitted for certain registered industrial uses (electronic industries, chlorine plants, paints, dental, etc.), although the declared uses from these industries are declining. It was estimated that in 1989, out of a total of 337 tonnes of mercury imported into Brazil, more than 170 tonnes was illegally diverted to mining activities, and subsequently lost to the environment (Ferreira and Appel, 1991). In 1998 and 1999, 90 and 50 tonnes of mercury products respectively, entered Brazil from Russia, Spain, Algeria and Finland (DNPM, 2000). The intensity of mercury use is further exacerbated by its low price. Even when sold in Brazilian *garimpos,* at five times the international price, mercury has a cost equivalent of 0.012 g of gold per tonne of ore processed (Veiga & Fernandes, 1990).

Gold extraction using mercury consists of four main steps: amalgamation, separation of the mineral portion, amalgam decomposition and gold melting. A common practice during the gold rush in the Amazon involved amalgamation of the whole ore, either by spreading mercury on the ground, on riffled concentration boxes or carpets. As mercury amalgamates with gold, the heavier amalgam 'sinks' and is retained behind riffles or in carpet fibres. As copper also forms amalgams with mercury, copper plates are alternately used to retain the Au-Hg amalgam. When using hydraulic monitoring, which involves the 'fluidization' of loosely consolidated materials with water, some miners spread large amounts of mercury on the ground, in the belief that the 'quicksilver' will move throughout the dirt and capture all available gold. When this crude method is used, losses are higher than 3 parts of mercury lost to 1 part of gold produced. Fortunately, thanks to the influence of public opinion and artisanal miners' associations, this practice is rarely or no longer used in the Brazilian Amazon.

In dredging operations, such as those carried out on the Madeira River, gold-containing sediments are pumped from river the bottom, and amalgamation is effected on board rafts with a high-speed blender. These operations continually discharge mercury-rich amalgamation tailings into the rivers (Pfeiffer et al., 1991).

Currently, most miners only amalgamate gravity concentrates (i.e. ore which has been crushed and separated by weight), a practice that contributes to significant reductions in mercury consumption and emissions. Approximately 14 grams of mercury are required to amalgamate 1 kg of concentrate (ratio Hg:conc.=1:70). The undesirable mineral portion is separated from the Au-Hg amalgam by panning either in 'waterboxes', in pools excavated in the ground or at creek margins. The heavy mineral-rich amalgamation tailings frequently contain 200 to 500 ppm of residual mercury, which create 'hot spots' when discharged into adjacent water bodies.

Excess mercury is removed from the amalgam by an ancient process of hand-squeezing filtration using a piece of fabric. The excess mercury is re-bottled and used again. Once the amalgam is obtained, which typically contains ~60% gold, it is retorted or simply burnt in pans. A retort is a container in which the Au-Hg amalgam is placed and heated; volatile Hg travels up through a tube and condenses in an adjacent cooler chamber. More than 95% of the mercury can be recovered through retorting, and this method therefore contributes to significant reductions in air pollution and occupational exposure. Unfortunately, the method most commonly used by artisanal miners is direct open-air burning of the amalgam in a pan or shovel using a blowtorch (Plate 3) -- as it is fast and easy. When retorts are not used, as much as 50% of the mercury from the amalgam is lost to the atmosphere and can accumulate in miners' lungs. When amalgamation is conducted properly using retorts, very little mercury is lost to the environment -- as little as 0.05% (Farid et al, 1991). The amalgamation methods used in *garimpos* vary, which together with the fate of contaminated tailings and Au-Hg separation procedures, define the extent of Hg losses (Table 3 and Fig. 1). Mercury volatilized in open pans rapidly condenses and is primarily deposited in nearby terrestrial and aquatic ecosystems.

The amalgam decomposition process (with or without retorts) produces a sponge-like gold *doré* containing about 20g of mercury per kg of gold. This is sold to gold shops in nearby villages or melted on-site to get rid of the remaining mercury and any other impurities. Mercury

Plate 3. A miner burns mercury from the gold amalgam.

Table 3. Influence of type of amalgamation method on mercury losses to the environment

Amalgamation method	Hg_{lost} : $Au_{produced}$
Whole ore	3
Concentrates, no retort	1
Concentrates with retort	0.001

levels inside melting sheds are extremely elevated. Fume hoods – if they are used at all -- are usually rudimentary, consisting of only a fan that blows mercury vapours into the ambient atmosphere. As evidence suggests that most volatilized mercury is deposited near the emission source, exposure to mercury vapour is extremely high for people living in close proximity to gold smelters.In a study by Marins et al. (1991), most of the Hg emitted from the 32 gold smelting shops was deposited near the emission source (i.e. within 1 km); this is consistent with other research (CETEM, 1991). Borochoff (2001) also believes that mercury vapour emitted from gold mines and gold shops is not transported more than 2-3 km, mainly because it is at a relatively low temperature and remains controlled by lower, local wind currents. This is consistent with results from Alta Floresta, a town in the south of the Amazon Basin, where analyses of air and soil samples taken up to 500 m from gold shops did not show significant Hg concentrations (CETEM, 1991).

An example of effective and creative amalgam processing is currently being applied in Venezuela, where amalgamation centres have been constructed to increase gold recovery and reduce mercury emissions. Miners bring their gravity concentrates to these private or state-owned centres to be properly amalgamated, retorted and melted by specialized operators (Veiga, 1997).

Evaluations at different *garimpos* have shown that around 70% of total Hg lost to the environment from artisanal mining operations is released when the amalgam is burnt in open pans, 20% is discharged with amalgamation tailings, and 10% is released to the urban atmosphere when gold dealers melt the bullion without appropriate fume hoods (Farid et al, 1991). It is apparent that the processing method employed by artisanal miners has a major impact on the level of pollution and related impacts to ecological and human health at both active and abandoned sites.

2. Abandoned artisanal mines – causes and consequences

The environmental and socio-economic impacts of artisanal mining and mine abandonment can be devastating to dependent communities. The primary reason why abandoned artisanal mining sites are highly contaminated with Hg is insufficient technical knowledge on the part of the miners combined with a lack of official policies to assist them. To better understand why these

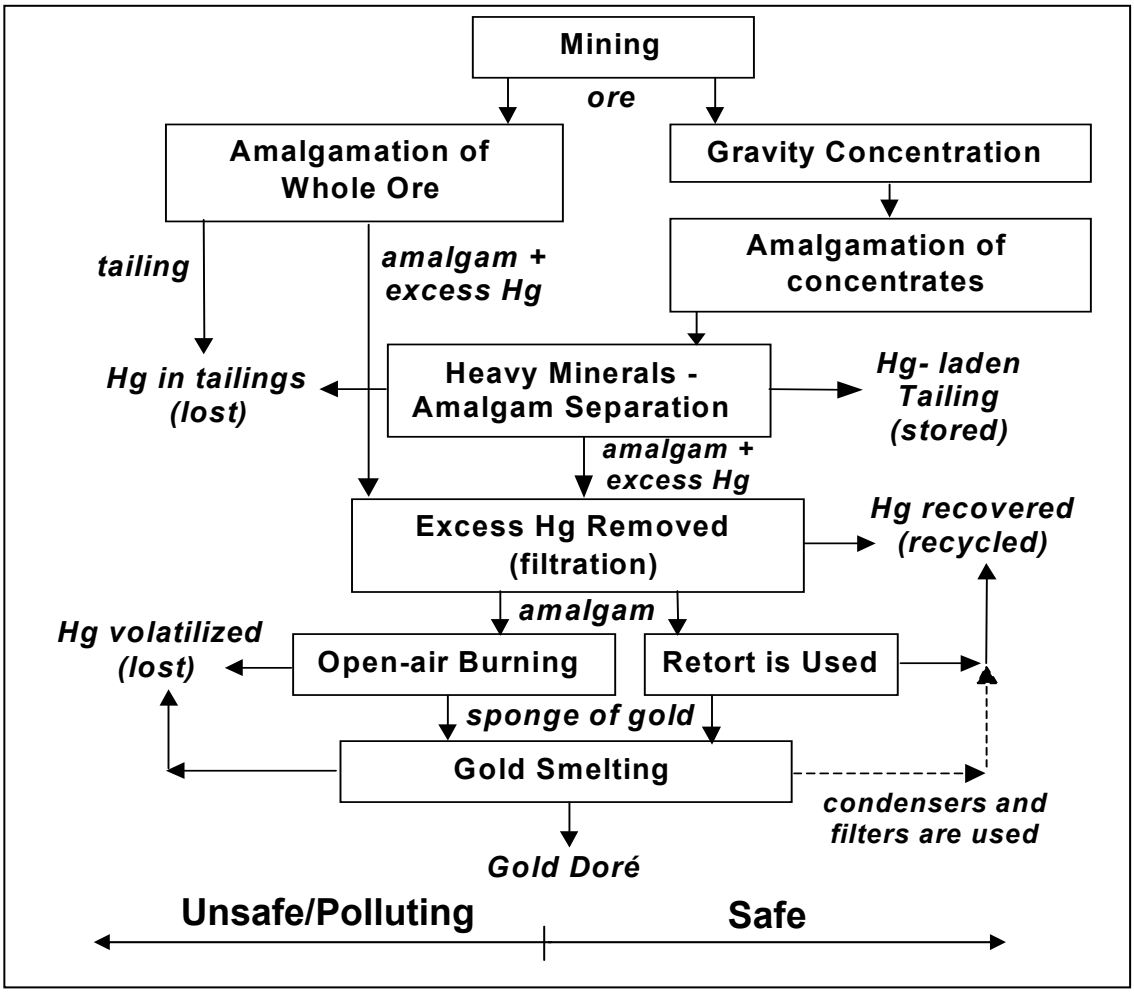

Fig. 1. Main steps involved in gold recovery by amalgamation in artisanal mining. The right side of the graphic consists of operations that can reduce Hg emissions.

unsustainable practices persist, it is necessary to explore the causes of mine abandonment. The causes and consequences of artisanal mine abandonment are illustrated in Fig. 1 and discussed in greater detail below.

2.1 Causes

2.1.1 Depletion of easily extractable ore

As it is believed that most of the easily accessible and extractable surficial deposits have already been identified in the Amazon, it is anticipated that there will be very few new artisanal mines in the future. Hard rock deposits, which sometimes underlie surficial ones, are far too complex and technically demanding for these miners and, once encountered, signify the beginning of the end of the artisanal operation. As surficial deposits are depleted, miners migrate to other regions and often cross borders into neighbouring countries, sometimes creating international conflicts. It is estimated that, in Suriname, for example, between 15,000 and 30,000 artisanal miners are illegal immigrants from adjacent countries, such as Brazil (Veiga, 1997).

2.1.2 Legislation and regulations

A variety of low-cost measures exist that would reduce mercury missions, such as the distribution of simple home-made retorts (Veiga, 1997) or more efficient processing equipment that would reduce the volume of concentrate to be amalgamated, or the establishment of processing and amalgamation centres. However, as the use of mercury for mining is illegal, most federal and local governments are hesitant to introduce alternative (mercury-based) techniques. The few initiatives that have been implemented have not had a lasting impact (CETEM, 1991; 1993; 1995). In addition to the lack of technical support, criminal activities like money laundering, prostitution and drug abuse are often rampant and law enforcement of these activities - as well as of illegal use of mercury - is nearly impossible, particularly in remote regions.

Although the importance of regulating the artisanal mining sector is recognized by legislators (Barreto, 1993), artisanal miners are not properly considered within the legal framework. Fundamental factors that impede the development of suitable legislation include an inability to

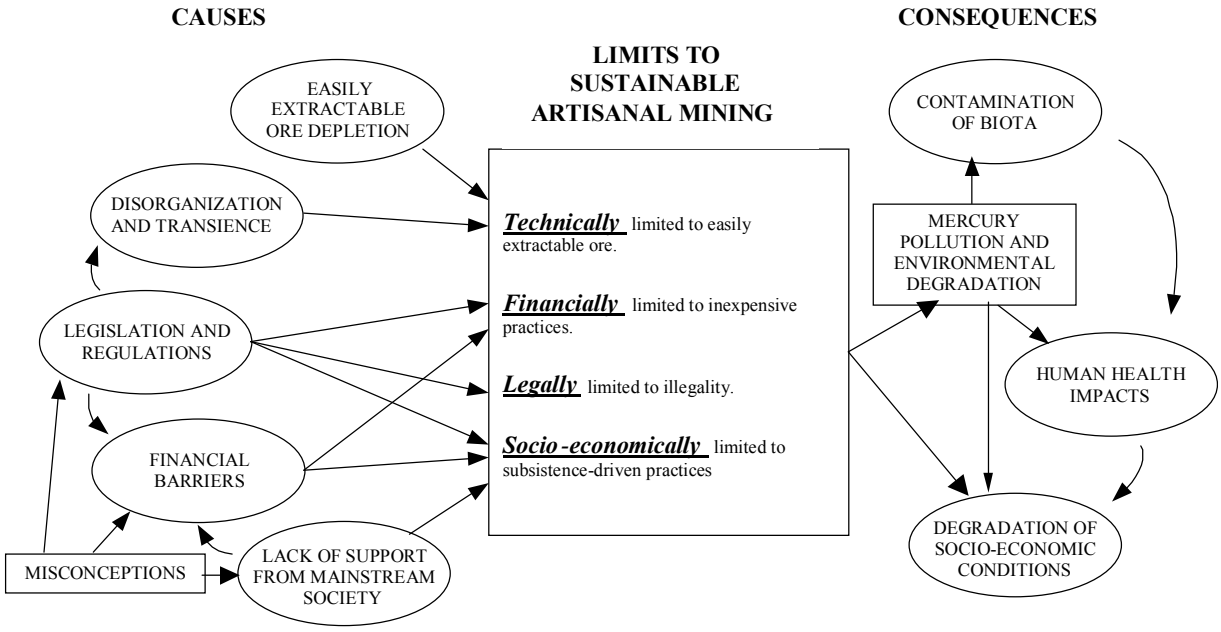

Fig. 2. Causes and consequences of artisanal mine abandonment

come to agreement on how these activities should be defined and licensed, i.e. on the basis of operation size, mineral extracted, income generated, degree of mechanization, etc., and inadequate government resources to enhance artisanal miners' capacity to understand and adhere to legislative measures.

The limited success of past regulatory efforts is exemplified by Decree 98,812 of January 1990, which limited the locations where artisanal miners could work in Brazil. Artisanal mining is only accepted in the *Reservas Garimpeiras* (reserves for *garimpagem*) and a special permit to work (*lavra garimpeira* permit) must be obtained from the Brazilian Mineral Production Department (DNPM). To obtain this special permit, an individual must present an elaborate environmental impact assessment, a necessary, albeit complicated, obstacle for most unorganized miners. After more than ten years, it seems that the idea of designating specific sites for artisanal miners has been beneficial to only the few organized and privileged miners capable of satisfying the bureaucratic requirements of the permitting process. With no technical support -- despite the good intentions of this decree -- the social and environmental problems and poor practices persist in these reserves.

In 1995, the World Bank concluded that none of the problems related to artisanal mining could be effectively tackled until a prime need were met: legal titles (Barry, 1996). If appropriate legal titles were designated and granted to artisanal miners, the miners would be able to negotiate with companies and transform a site into a formal operation. They would also be required to satisfy legal requirements for responsible reclamation and environmental practices. Ultimately, however, if mining within a regulatory framework is not obviously advantageous to miners, they will inevitably choose to work outside the system (Bugnosen et al, 2000).

2.1.3 Financial barriers: market prices, taxes and operating costs

Artisanal miners certainly are not exemplary taxpayers. Motivated by better gold prices, they commonly cross borders and their citizenship can be unclear. The frequent border crossing has contributed to the emergence of a black market within many Latin American countries. For example, Uruguay, which is not a gold-producing country, exported 29.4 tonnes (945,000 oz) of gold in 1984, the bulk of which most likely came from the Brazilian Amazon via São Paulo (Cleary, 1990).

In addition, the low market price of gold (approximately US$270/oz) together with the high cost of fuel in Brazil, has resulted in reduced profit margins. In this situation, it is probable that the quantity of undeclared – and thus non-taxable -- gold has increased. In such a scenario, it is even less likely that funds are allocated to safety or environmental protection. Actually, when operating costs increase, miners tend to use more mercury in the hopes of increasing gold production.

2.1.4 Lack of financial and technical support from mainstream society

For developing countries, artisanal mining contrasts strongly with the concepts of modernity and efficiency pursued by mainstream society. The acquisition of technical support, essential to improve gold recovery and take appropriate measures for environmental management requires financing. However, artisanal miners do not have access to banks or lending institutions, primarily due to lack of collateral.

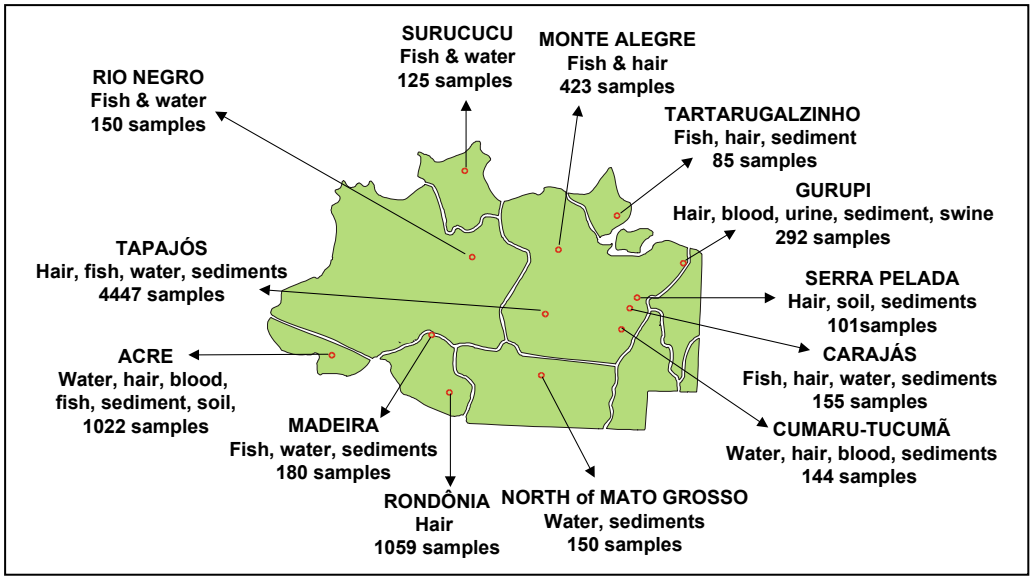

Fig. 3. Geographic distribution of samples collected in the Amazon Region for mercury monitoring.
Source: Alberto Rogerio B. Silva (1999)

Furthermore, as they are not a source of tax revenue for the government, they have little political influence; this is reflected in the ineffective government policies in the sector.

The lack of support for artisanal miners is exacerbated by the complicated and potentially harmful nature of mercury. In 1991, Ivo Lubrina, president of the Amazonian Union of *Garimpeiros* (USAGAL) declared in an interview (Lobato and Barbosa, 1992):

> "Thanks to radio and TV, *garimpeiros* are concerned now about mercury, but they don't know exactly why. As there is no orientation from government or technical people, everything continues as before. I would say that the transfer of news among *garimpeiros* is happening like a hot potato: it is going from one hand to another".

Although most Brazilian states in the Amazon region have environmental agencies, these are inadequately funded and lack technical expertise, which hampers the implementation of educational initiatives about mercury and its impacts.

When artisanal miners start working with primary ores (e.g. sulphide associated gold, often found at depth) they require substantial investment and greater technical capabilities. When production levels are lower than from secondary ore, miners first use greater quantities of mercury and later seek technical assistance. Normally, this support is not available. Engineering companies usually refuse to help artisanal miners and hiring consultants is too costly. Local governments are not prepared to provide specialized personnel or appropriate technology, and research institutions primarily offer high-tech methods.

The few support programmes that have been conducted have focused on reducing mercury emissions and providing safe technologies for miners. On the other hand, universities, research institutes and international agencies have allocated considerable resources to monitoring programmes to measure levels of mercury in sediments, air, water and biota at active and abandoned artisanal mines. Alberto Rogerio B. Silva (1999, personal communication), former director of the Secretariat of Industry, Commerce and Mining in the State of Pará, gathered results of 8,333 samples of sediments, water, and biological subjects from at least 30 research institutes around the world (Fig. 3). The Amazon region has been used as a living laboratory for academic researchers. In many monitoring programmes, human beings are seen merely as donors of hair, blood, or urine samples. In most cases, affected people never learn the results of the monitoring programme, unless, of course, they read the scientific literature. The number of researchers focussing on highly specific scientific mechanisms is far greater than those investigating or implementing solutions (virtually none).

2.1.5. The disorganized and transient nature of artisanal mining

Most artisanal mining operations are highly uncoordinated, with miners working essentially independently of one another or in small partnerships. However, informal working agreements can also be found (MacMillan, 1995). ‘Owners’ allocate plots, collect taxes, and charge fees for services such as transportation, goods and services, including food to miners who migrate to newly discovered deposits. Of course, the remoteness of the site dictates the price of these services. As the owners are usually ‘rich’ foreigners, in many cases airplane pilots, they do not establish any lasting labour relationships or long-term commitment to the site or surrounding community. Actually, they tend to hire miners for short periods of time and pay based on a percentage of the daily gold production.

With improved access to financial resources and other support systems, small partnerships and cooperatives could be formed, thereby contributing to the formalization of operations (Barry, 1996). This formalization would be conducive to operating within a regulatory framework – an important component of mitigating the environmental and socio-economic impacts of these activities. It has been reported that international charities and religious organizations have financially supported the development of artisanal mining associations or cooperatives in several countries (Davidson, 1995). However, as most artisanal mining partnerships have been somewhat superficial - developed to generate revenue rather than true collaborations on a technical or financial level - it is apparent that any organizations formed needs to be well structured, accompanied by technical or financial support, and be of obvious long-term benefit to participating miners. As it is well demonstrated that programmes developed by the people participating in them (i.e. bottom-up measures) tend to be most effective and enduring, any measures to support formalization and related development initiatives should be driven by members of the artisanal mining community.

2.1.6 Perceptions and misconceptions

The general population is unaware of the unpredictable nature of mercury, artisanal mining activities and conditions in these communities. Artisanal mining represents a very labour-intensive, low-tech activity that mainly takes place in marginalized communities. In addition, individuals in positions of political or economic influence tend to be negatively biased towards artisanal mining and may manipulate public perception about the activity for their own gain. Thus, government policies do not effectively address the realities of artisanal mining.

Inaccurate or exaggerated portrayals of these activities and the effects of mercury have, at least in part, perpetuated biased perceptions of artisanal mining. On a Brazilian TV show in 1987, José Altino Machado, a veritable leader of artisanal miners, was verbally attacked by participants in a forum on artisanal mining. During an ecologist's impassioned speech about the dangers of mercury, José Altino took the vial of 'deadly' metallic mercury held by the ecologist and swallowed it to demonstrate its harmlessness. Of course, the environmentalist and many viewers were unaware that the toxicity of metallic mercury by ingestion is relatively low. In another example, in 1989, a Brazilian research centre began a series of studies in the western part of Brazil to investigate whether mercury from artisanal mining was contaminating biota (CETEM, 1989). When the research team arrived in the municipality of Poconé, State of Mato Grosso, fish consumption had declined and mineral water sales increased substantially. It was later discovered that unfounded rumours concerning mercury contamination of water and fish were actually spread by mineral water company representatives and local butchers.

Governments can also perpetuate negative perceptions for political gain. In 1990, newly elected Brazilian President Fernando Collor de Melo declared his intentions to expel artisanal miners from the proposed 9.4 million hectare Yanomami reserve. Federal police cleared operations, destroyed equipment and dynamited airstrips, thereby "draining the momentum of the gold rush." Numbers operating in the reserve dropped to 2000 in 1992, but again escalated to 11,000 in 1993, demonstrating the futility of this action in the absence of economic alternatives for miners (MacMillan, 1995).

It is evident that the elements contributing to the abandonment of artisanal mines are intrinsically linked. Although depletion of an ore body is uncontrollable, the degree to which a body can be exploited depends on technological and financial capabilities and the ability to operate in a highly organized and safe manner. Environmental and socio-economic conditions at these mines, during operation and beyond, rely on the presence of a legal framework with regulations coupled with technical education/information programmes and economic incentives. As demonstrated in the Yanomami reserve, miners will certainly return to illegality and any initiatives, such as those related to responsible environmental practices (e.g. reclamation, processing methods), will remain ineffective unless accompanied by opportunities for financial gain.

3. Consequences

All causes discussed seem to increase the probability for an artisanal mine to be abandoned. It seems, however, that negative and inaccurate perceptions held by governments and civil society have been the primary inhibitors to breaking through the technical and financial barriers to a socially and environmentally responsible artisanal mining sector. Consequently, affected communities have been ignored and mistrust towards outside parties remains high. Mainstream society is hesitant to support initiatives that further artisanal mining and miners are suspicious of and unlikely to employ externally derived solutions for technical or socio-economic problems. Thus, environmental degradation continues, and tragic socio-economic conditions persist. The legacy of these activities can be severe: as mining activities cease, social and economic systems in artisanal mining communities inevitably change and become extremely unstable. Environmental impacts, such as deforestation and river siltation, can damage fisheries and whole ecosystems. Although social impacts are often of greatest concern, one of the most significant and persistent *environmental* impacts in artisanal gold mining is related to mercury, which can reach aquatic systems, enter the food chain and detrimentally impact human health.

3.1 Mercury pollution

Artisanal gold miners discharge large quantities of mercury into the atmosphere, soil and aquatic systems, where it can

be transformed into compounds of varying toxicity that may ultimately impact human populations. Although mercury may be relatively immobile in soils, once it reaches an aquatic system, it is subjected to a number of chemical and biological factors (e.g. pH, organic matter, and oxygen content), that can modify its form and enhance its mobility or bioavailability. In sediments, metallic mercury can be oxidized and transformed into methylmercury (CH_3Hg), a highly toxic and readily bioavailable form of organic mercury (i.e. a form that can be assimilated by organisms).

Methylmercury constitutes a large fraction of total mercury in living organisms. Once mercury enters biota (e.g. plants, animals), concentrations generally increase up levels of the food chain (i.e. it is biomagnified). Consequently, carnivorous fish from impacted areas are most likely to have high mercury concentrations. Not surprisingly, inhabitants of communities dependent on mercury-laden fish as a primary food source frequently have elevated mercury levels in blood. Although people prefer to consume better tasting carnivorous species, mercury impacted riparian communities must understand that herbivorous fish should be preferentially selected for consumption. Educational programs communicating the hazards of contaminated fish consumption and highlighting potential local alternatives have been proposed and implemented to reduce the risks from fish consumption when warranted.

A ratio of $Hg_{lost}/Au_{produced}$ is frequently used to estimate the amount of mercury discharged into a given environment. As discussed, this ratio typically ranges from 1 to 3 depending on whether unprocessed ore or concentrate is used, and whether a retort is used (see Table 3). This ratio was statistically derived from data from a number of operations. In reality, at some locations, significant quantities of mercury can be used and discharged without any appreciable gold recovery. So, although an estimated 20 tonnes of gold was produced in the Brazilian Amazon in 1999 (IBGM, 2001), it is reasonable to suggest that at least 20 tonnes of mercury was discharged into the environment in the region during that year alone. Although artisanal gold production has decreased significantly since the 1980s (compare with 64 tonnes in the same region in 1983), these outputs are nevertheless quite substantial. Estimates derived by Lacerda and Marins (1997) suggest that emissions from mining are around 78 tonnes per year. An estimated 3000-4000 tonnes of mercury have been emitted into the environment from artisanal mining activities in the Brazilian Amazon alone in the last two decades (Veiga *et al*, 1999).

Mercury persists in tailings, soil, sediment, water and biota (plants and animals) but can be mobilized over an extended period of time by volatilization (i.e. evaporation) or reaction with organics.

Volatilization and atmospheric transport to relatively distant regions or countries is probable (Villas Boas, 1999), particularly in association with forest fires. Forest fires are responsible for mobilizing extensive amounts of mercury contained in biomass as well as the mercury emitted by miners and deposited nearby (Meech et. al., 1995). Due to the high rate of deforestation by fire in the Amazon [29,059 km² in 1995 (Artaxo et al, 2000)], mercury emissions from wood combustion have been estimated at between 0.78 and 1.76 kg/km² of forest per year (Veiga et al., 1994; Lacerda 1995). Through analysis of aerosol particles, Artaxo et al. (2000) estimated that about 30% of the Hg emitted in the Amazon region is associated with biomass burning and 63% from gold mining.

The presence and abundance of organic matter, which is characteristic of Amazonian 'darkwater' systems, can significantly influence the mobility and bioavailability of metals. Soluble organic acids (decomposed plant residues) tend to form soluble complexes with mercury, transporting it over great distances in water systems. Metallic mercury from discharged tailings can react with organic acids (Tromans et al., 1996), thereby producing potentially mobile complexes. Evidence also suggests that mercury associated with organics can be methylated by bacteria in sediments or directly within the intestines of some organisms (Veiga et al, 1999). In vegetation rich surroundings, reactions with organic acids are probable and the methylation potential is therefore high. It is also reasonable to assume that atmospheric mercury deposited in remote dark rivers is highly reactive, which explains why mercury levels in fish from dark waters are considerably higher than in fish from clear waters poor in organic matter, even in the absence of nearby mining activities.

3.2 Human health effects

Mercury is widely recognized as one of the most toxic metals known to man. Although elemental mercury vapour can pose a serious health risk if inhaled, organic forms of mercury, specifically methylmercury is of greatest concern in terms of exposure from food.

Artisanal miners involved in amalgam decomposition through open-air burning and working or living in close proximity to gold shops are at a significant risk of mercury poisoning. Inhaled mercury is oxidized in the lungs forming blood-soluble Hg (II) complexes (Jones, 1971), which can readily penetrate the brain (Chang, 1979). The kidneys are the affected organs in exposures of moderate to significant levels, while the brain is the dominant receptor in long-term exposure to low or moderate levels of mercury vapour (Suzuki, 1979). The symptoms usually associated with chronic Hg vapour exposure are erethism (exaggerated emotional response), gingivitis and muscular tremors. Mild cases of mercury poisoning have many psycho-pathological symptoms that can be mistaken for alcoholism, or fever, malaria or other tropical diseases.

Many years after mining operations have ceased, metallic mercury can be transformed into methylmercury through biologically mediated reactions. Intestinal adsorption of methylmercury from fish ingestion is extremely high and chronic exposure to moderate levels

results in symptoms including: visual constriction; numbness of the extremities; impairment of hearing; impairment of speech; and impairment of gait. In cases of acute intoxication, muscular atrophy, seizures and mental disturbance are prominent.

Women of childbearing age and their children are particularly susceptible as methylmercury readily crosses placental barriers and is considered to be a developmental toxicant (Grandjean, 1999). Depending on the frequency and degree of exposure, effects can range from sterility, spontaneous abortion, to mild to severe neurological symptoms.

3.3 Other environmental issues

A number of other ecosystem impacts, such as water siltation, extensive deforestation and modifications to hydrologic regimes, can result from artisanal mining activities. For instance, it is estimated that up to 2300 km^2 of forest in Suriname alone will be destroyed by artisanal miners by 2010 (Peterson and Heemskerk, 2001). Ranching continues to be the primary cause of deforestation in the Amazon (MacMillan, 1995). Despite the importance of these impacts, they are beyond the scope of this review.

3.4 Degradation of socio-economic conditions

A number of transformations occur in the community as artisanal mining activities subside. Violence and prostitution may decline with the out-migration of miners, but any indications of former wealth also tend to disappear. Consequently, it is even more unlikely that any resources would be allocated to environmental protection and remediation. Furthermore, with the transition to agriculture, additional deforestation from slash and burn practices can occur, thereby releasing additional mercury into the atmosphere. When mining activities cease and economic conditions decline, government intervention may certainly be needed; however, this degradation could likely be avoided if involvement occurred prior to abandonment.

4. Conclusion

The health and welfare of millions of Amazonians are directly and indirectly influenced by artisanal mining activities. Artisanal gold mining is a temporary activity, which continues until deposits of easily extractable gold are exhausted. The rudimentary methods, characteristic of artisanal mining, often generate extensive environmental degradation that persists long after mining activities cease. Although the use of mercury is illegal in Brazil, due to its simplicity mercury amalgamation is the preferred method employed by artisanal gold miners.

Pressure from international environmental groups has compelled the Brazilian Government to attempt enforcement of laws against miners. However, the government's primary response is rhetorical, ignoring the situation, mainly because it cannot provide the social services and economic stimulation to replace the positive economic benefits previously generated by artisanal mining. It is clear that problems associated with artisanal mining activities are not generated by conflicts between humanity and nature, but between people at the bottom of society's hierarchy versus those on higher levels.

Solutions to the mercury problem have been discussed throughout this article. From the use of retorts to processing-amalgamation centres, from educational campaigns for miners to health and nutritional advice, e.g. regarding consumption of fish; from the use of Hg-free techniques to clean-up processes; from employment alternatives to creation of sustainable communities, from organization of mining activities to access to mineral titles, there are a number of measures which can be implemented in order to directly or indirectly reduce the effects of the mercury pollution. However, it is apparent that political will is the most important influence on positive action. As law enforcement has been ineffective in controlling artisanal miners, it is clear that a different approach is needed, one in which government together with civil society find technical and legal solutions. If sufficient pressure is not applied on the Brazilian government to address these issues and intervene immediately, the cycle of artisanal mining is doomed to continue, inevitably contributing to a legacy of mercury pollution of a magnitude even greater than what has been documented to date. It has been 20 years since the mercury problem was first identified, but still nothing constructive has been done.

Mercury and mercury-rich tailings from past and current mining operations have been discharged directly into watercourses from thousands of artisanal gold mining sites. This exacerbates the potential for its incorporation into the food chain, thereby posing a serious risk to human health. Urgent action is needed to identify sites with extensive contamination and apply remedial measures to avoid the transformation of this metal into more insidious and bioavailable forms.

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