A BRIEF HISTORY OF AMALGAMATION PRACTICES IN THE AMERICAS

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ABSTRACT

The ability of mercury to form amalgams with gold and silver has been exploited by man since antiquity. Only in recent years have we recognized the significant danger of this metal to accumulate in food web and cause health problem. This paper presents a brief overview of the use of amalgamation in North and South America for gold recovery from ores and concentrates. The widespread reliance of "informal" gold miners to use this process suggests that its rapid demise is only hopeful thinking. Instead, "safe" methods must be promoted among the miners through education and demonstration.

MERCURY, A HOLY MEDICINE

Mercury is the 7th metal of antiquity and has been known and used for more than 3500 years. Samples of mercury were discovered in ancient Egyptian tombs that date to 1500 or 1600 BC. The first reference to metal extraction in written records is attributed to Aristotle in the 4th century BC. Romans used cinnabar (HgS) for writing their books and as a pigment to decorate tombs, statues and walls. They also used elemental Hg as an amalgam to separate gold from other materials and as an amalgam to coat gold onto copper (Nriagu, 1979; D'Itri, 1972).

The chemical symbol of mercury, Hg, comes from the Greek name Hydrargyrum (liquid silver) and the name Mercury was given by medieval alchemists after the fleet-footed Greek god. In 1533, Paracelsus wrote a book about occupational diseases in which he described in detail Hg poisoning of miners. Although Paracelsus was intrigued with Hg, he considered it a metal that was deficient in its coagulation ability. He believed that all metals were liquid Hg up to the midpoint of the coagulation process. Consequently, he expended much unsuccessful effort trying to coagulate Hg to convert it into gold (D'Itri, 1972).

Inorganic Hg compounds have been used extensively as antiseptic, disinfectant, purgative, and counterirritants in human and veterinary medicine. Various Hg compounds
were developed to aid in the control of bacteria, fungi and other pests. Paracelsus introduced probably the most unusual medicinal use for Hg. He dissolved Hg in oil of vitriol (sulphuric acid) and distilled the mixture with Spiritus vini (alcohol) as a cure for syphilis. This use of Hg persisted until the 1930s (D'Itri, 1972). Many of these applications are gradually being replaced by other compounds.

AMALGAMATION IN NORTH AMERICA

The extraction of gold by amalgamation was widespread until the end of the first millennium. In the Americas, mercury was introduced in the 16th century to amalgamate Mexican gold and silver. The Spanish authorities encouraged mercury ore prospecting in order to supply the Californian mines. In 1849, during the American gold rush, small mercury deposits were exploited. At this time, mercury was widely used by American miners (prospectors) in their pans, sluices, etc. Mercurialism became a common illness among the cinnabar miners and gold panners (D'Itri and D'Itri, 1977).

Buhler et al. (1973) make reference to 7 - 30 g of Hg discharged in the waste water per tonne of gold ore processed by miners in the 1860s in Southern Oregon and Idaho.

In Quebec, Canada, old gold mines in Val d'Or used amalgamation throughout much of the 20th century. Today most abandoned sites show high Hg content in sediments (up to 6 ppm) and in fish. As a result of chemical analysis of fish muscle, it was observed that bioaccumulation is related to food web and fish age. A total of 31 specimens of pike showed an average level of 2.6 mg/kg (ppm) - more than 5 times above the guideline level. All fish collected upstream of tailing ponds along the rivers Colombière and Bourlamaque contain more Hg than do the fish collected downstream. These are darkwater rivers and explanations for these phenomena are still being researched (Poirier, 1993, Louvicourt Project - personal communication).

Lane et al. (1989) studying plants as a mercury indicator in old gold tailings in Nova Scotia, found Hg in leaves ranging from 0.18 to 0.55 ppm; although roots showed values up to 6.1 ppm. Such high levels in roots suggest that a process of bioaccumulation is occurring.

In Yellowknife, NWT, the impact of the use of Hg in gold amalgamation from 1950 to 1969 in the Discovery Mine site, is mirrored today by high Hg levels in fish of Giauque Lake. About 2.5 tonnes of Hg were discharged together with tailings. Due to the extent of Hg contamination, Giauque Lake has been closed to sport and domestic fishing for several years and has been described as a contaminated site under the Environment Canada National Contaminated Site Program (Baker et al, 1992).
Mudrock et al. (1992) investigated the effect of heavy metals in biota of past gold mining activity in the Cariboo region. In Jack of Clubs Lake, Wells, British Columbia, an old operation used amalgamation from 1933 to 1966. The Hg concentration in trout has been shown to exceed the 0.5 ppm Hg guideline for human consumption. The authors concluded that limited information is available on the effects of the abandoned gold mine tailings on the Fraser River Basin ecosystem.

The Pacific Northwest is situated in one of the major mercuriferous belts of the earth. Mercury was mined in the past in some parts of California and in Pinchi Lake, British Columbia. High levels of Hg in soils are related to organic matter. Background levels around 0.5 ppm in sediments collected at depths greater than 15 cm are reported in Washington State (Bothner and Piper, 1973). As mercury was used in the 1850s in gold mining operations, some authors have doubts about the origin of Hg in water, sediments and fish samples from Northwestern America.

Analyses of surface horizons of peaty-muck soils and those predominated by vegetative litter in British Columbia indicate an average of 165 ppb Hg and as much as 740 ppb Hg in non-mineralized areas. In the vicinity of Pinchi Lake (1 km) surface soils show lower values (750 ppb) than deeper horizon (25 cm = 2320 ppb Hg), although most sites not directly related with mercury ore deposits show 1/4 the concentration of those in surface litter, such as samples from the Fraser Valley (John et al., 1975). No correlation was found between Hg and organic matter analyzed in these soils, but surface soil was identified as the main Hg source. Sometimes statistical correlation between only two natural variables is not enough to explain an association. In this case, soils containing up to 70% of organic matter obviously play an important role in Hg adsorption although other variables such as microbial activity, mineral composition, pH, salinity, etc. also influence the relationship between two specific variables such as Hg and organic levels.

Garrett et al. (1980) also reported high Hg concentration in many areas in the Yukon Territory and in British Columbia. Levels up to 5.2 ppb Hg in surface waters were analyzed. The source of these high levels is not well understood.

The amalgamation process was widely used by Canadian miners in the 1860s until 1890s as observed in the reports of the Minister of Mines. Nuggets had a better price ($16.5/oz) than fine gold (MMBC, 1881) and mercury became a solution to extract fine gold from benches of the Fraser river extending from Hope to Lillooet. The text below extracted from MMBC (1875) shows clearly this fact: "... On the bars near the mouths of rivers, it is found in a fine impalpable dust, known as flour gold, and can only be collected by the aid of quicksilver."
Mercury was used in sluice boxes or in copper plates. It is reported that native Indians and Chinese were the best gold savers at that time. These latter were usually hired by the "white men" and then began their own operations later (MMBC, 1881).

Archives from British Columbia report the use of 25 lb of mercury per day per sluice by the old American and Canadian miners at Cariboo goldfields (1856).

Currently, amalgamation practices in North America are restricted to small operations. However, hundreds of thousands of booklets such as "Gold Panner's Manual" (Basque, 1991) are sold in Canada and USA, suggesting a simple way of separating gold and mercury by "baking" amalgam in the cavity of a scooped potato. It was also observed in small operations in British Columbia that another popular process to separate gold from amalgam is by using hot nitric acid solution - 30% vol.

In order to evaluate mercury contamination at an old mining site in Western Canada, we conducted a quick geochemical survey at Port Douglas. This site was a small village founded in the late 1850s at the tip of Harrison Lake, British Columbia to serve as the transit jump-off point to Cariboo goldfields. In 1859 more than 30,000 miners passed through the town. Primitive panning methods and sluice boxes were used to extract gold from the Lillooet River Delta by these pioneers but the Cariboo discoveries in the late 1860s meant the death knell for Port Douglas (Edwards, 1977; Basque, 1993). Some spot endeavours lasted up to 1920 but little information about gold output from this region is available.

The Lillooet River placer deposit is situated in the Canadian Cordillera Coast belt tectonic division where the gold is associated in quartz lodes emplaced in fissures and shear zones. The host environment contains altered Upper Paleozoic to Upper Jurassic eugeosynclinal or arc-type and volcanic rocks adjacent to plutonic complexes of varying size and composition. The placer gold is in part a product of aggradation of lode deposits, but precipitation of gold and mercury from hot springs may be a feasible process as well. (Steiner, 1983; Whitten and Brooks, 1988).

Soil and creek sediment samples collected around Port Douglas (today a camp of a gold exploration company) were analyzed. Some samples, a mixture of bottom sediments, were wet screened (no new water added) on a nylon 200 mesh (0.074 mm) screen in the lab. The -200 mesh fractions were filtered through a coarse filter paper then followed by a 0.45 μm Millipore® filter. Mercury in solids (dried at 60°C) and water was analyzed by flameless atomic absorption spectrometer (AAS). Gold in solution was determined by induction plasma spectrometer and in solids by aqua-regia attack + MIBK extraction and AAS readings (analyses performed at Quanta Trace Lab, Burnaby, Canada - liquids and solids - and CETEM - Centre of Mineral Technology, Rio de Janeiro, Brazil - some solid samples).
The presence of Hg droplets can be seen in sands from the Lillooet River. During gravity concentration of placer ore in a shaking table, small mercury beads are frequently observed in the concentrates. Natural amalgam in this placer occurs in the form of platy particles, with a paste consistency, very often stuck to gravel surfaces as observed under the optical microscope. Hot springs might be the main source of gold and mercury in the region and organic matter may have played a role in complexing and transporting Au and Hg in solution or as fine suspended particles.

Nugget formation from organic complexes has been observed in other placer deposits, such as Goodnews Bay, Alaska (Mardock and Barker, 1991). According to these researchers, humic acids transport gold and mercury, and amalgamation in the environment can account for subsequent accretion of gold. Metallic mercury is not very stable in organic-rich environment. It reacts with soluble organic humic substances to form complexes which can be transformed into methylmercury by biotic or abiotic reactions (Meech et al., 1995).

The results of the geochemical survey in Port Douglas may suggest an anthropogenic influence in several sites possibly exploited by the pioneers (Table I), however samples collected distant from Port Douglas, in sites unlikely worked in the past, also showed high Hg values (Table II). The majority of the samples are characterized by high organics (dark brown colour), 3.8 to 18.4% total carbon content, sometimes with the strong smell of hydrogen sulphide.

The sample from the Lillooet River delta (M17) showed an outstanding enrichment of Hg and Au. The black waters reached values around 2 ppb Hg and 20 ppb Au in solution or in colloids finer than 0.45 μm. These numbers are respectively 200 and 2000 times higher than the expected background for these elements in freshwater (Förstner and Wittmann, 1979). When samples rich in organics were subjected to extraction with caustic soda (5M NaOH), at 80°C for 2 hours, 30% of the Au and 50% of the Hg were extracted, indicating a strong association of these metals with organic matter, in spite of a weak correlation between total carbon and Hg content in the samples.
### Table I - Samples from Port Douglas with possible influence of old miners

<table>
<thead>
<tr>
<th>Sample</th>
<th>Water (&lt;0.45 μm)</th>
<th>Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hg (ppb)</td>
<td>Au (ppb)</td>
</tr>
<tr>
<td>M4 (-200#) - creek in Port Douglas</td>
<td>&lt;0.2</td>
<td>4.37</td>
</tr>
<tr>
<td>M4 (+200#)</td>
<td>na</td>
<td>3.62</td>
</tr>
<tr>
<td>M7 (-200#) - creek near the</td>
<td>&lt;0.2</td>
<td>3</td>
</tr>
<tr>
<td>M7 (+200#) - Little Harrison Lake</td>
<td>na</td>
<td>0.72</td>
</tr>
<tr>
<td>M8 (-200#) - creek 3km from P.Douglas</td>
<td>&lt;0.2</td>
<td>5</td>
</tr>
<tr>
<td>M8 (+200#)</td>
<td>na</td>
<td>0.73</td>
</tr>
<tr>
<td>M15 (+200#) - sand Sloquet creek</td>
<td>na</td>
<td>2.28</td>
</tr>
<tr>
<td>M19 (-200#) - creek 500 m from P.D.</td>
<td>2.6</td>
<td>15</td>
</tr>
<tr>
<td>M19 (+200#) - in front of an old hut</td>
<td>na</td>
<td>0.58</td>
</tr>
<tr>
<td>M20 (-200#) - same creek</td>
<td>na</td>
<td>3.0</td>
</tr>
<tr>
<td>M20 (+200#) - surface sample</td>
<td>na</td>
<td>1.54</td>
</tr>
<tr>
<td>M21 (+200#) - soil in P.Douglas</td>
<td>na</td>
<td>0.57</td>
</tr>
<tr>
<td>M22 (+200#) - Little Harrison Lake</td>
<td>na</td>
<td>0.49</td>
</tr>
<tr>
<td>M23 (+200#) - Little Harrison Lake</td>
<td>na</td>
<td>0.49</td>
</tr>
</tbody>
</table>

**Note:** na - not analyzed

### Table II - Samples from Port Douglas with unlikely influence of the old miners

<table>
<thead>
<tr>
<th>Sample</th>
<th>Water (&lt;0.45 μm)</th>
<th>Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hg (ppb)</td>
<td>Au (ppb)</td>
</tr>
<tr>
<td>M1 (+200#) - black sand Douglas creek</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>M3 (+200#) - organic matter-mountains</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>M10 - soil 0 - 1 m - 50 km from P.D.</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>M10 - placer - 1 - 3 m</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>M10 - placer - 3 - 5 m</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>M11 (+200#) - soil 28 km from P.D.</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>M12 - water from hot spring</td>
<td>&lt;0.2</td>
<td>2</td>
</tr>
<tr>
<td>M13 - drinking water from mountains</td>
<td>&lt;0.2</td>
<td>2</td>
</tr>
<tr>
<td>M14 - water 10 km from P.D.</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>M16 - bog water - Lillooet delta</td>
<td>&lt;0.2</td>
<td>2</td>
</tr>
<tr>
<td>M17 - bog water - Lillooet delta</td>
<td>1.9</td>
<td>24.0</td>
</tr>
<tr>
<td>M18 (+200#) - sand Lillooet delta</td>
<td>na</td>
<td>na</td>
</tr>
</tbody>
</table>

**Note:** na - not analyzed
AMALGAMATION IN SOUTH AMERICA

In South America, news about Hg use in gold operations is told by native engineers and geologists, but little is reported in the literature. In Peru, a current gold rush was triggered in Madre de Dios Department where about 10,000 "chichiqueros" (informal miners) have worked since 1990. About 130 kg of gold/month are recovered by similar methods used by Brazilian "garimpeiros" and Hg is extensively used and burnt (Bliss and Olson, 1992).

Amalgamation and cyanidation are practiced by informal miners in Ecuador in the cities of Zaruma and Portovelo. There are 68 plants in operation with a capacity to process 14,000 tonnes of ore/month. The ore is exploited through shafts to be crushed and ground in different mills (balls, rods, etc.). Concentration is carried out in sluices lined with carpets. The ore concentrates are amalgamated in a sort of "Muller" pan for 2 to 4 hours. Amalgam is usually burnt in pans, sometimes wrapped in aluminum foil. The gold production is estimated at 1.4 tonnes/year with recovery around 50 percent (Vaca, 1992).

In Brazil, the first gold cycle started in 1695 with discovery of gold close to Vila Rica (today Ouro Preto city), although there are reports of gold prospecting works dating back to 1552. This gold cycle was marked by the pioneers (so called "bandeirantes") who grubbed the western lands seeking and mining alluvial and lateritic gold (rich in nuggets) with rudimentary methods. There is no evidence of mercury use during this time. Amalgamation processes seem to be applied in the beginning of 19th century when British technology was imported to Brazil.

A second gold cycle is marked in Brazil and in other developing countries, at the end of 60s, by the end of the 1944 Breton-Woods agreements, which had held the price of a troy-ounce (31.1g) of gold at US$ 35 for a very long time. The price of gold gradually rose during the 70s, leading to the reworking of ores hitherto considered low grade.

CURRENT AMALGAMATION PRACTICES IN THE BRAZILIAN AMAZON

Most gold produced in the Amazon region comes from artisanal mining activities or "garimpos". "Garimpo" is a migratory activity which occurs due to lack of jobs or lack of gold. Since 1940 the Brazilian mining codes have shown preference to organized mining work over "garimpos". In the Constitution of 1967 the law determined that all "garimpo" activity must be stopped when a legal lease is conceded. Which activities should be considered "garimpo" and which are organized mining, has never been made clear, leading to misinterpretation. Classification of the types of minerals allowed to be mined by "garimpeiros" is only one source of misinterpretation (Barreto, 1991). As the ore is not always located totally within these reserves, the limits imposed by law have not been respected.
Illegal operations were flagrant across the country and ecologically sensitive areas received large squads of miners. Company leases were not respected either.

In the law 7805/89, the classification of "garimpo" is still attached to the type of ore deposit. The geological characteristic, by laws, delimits the type of work, or workers, applied to each kind of deposit. As placer and elluvial deposits imply a high risk for companies, the laws have tried to leave the risk with adventure-seekers. The transitory nature of this type of mining has always been the focus of Brazilian laws, however this is unrealistic. "Garimpeiros" have developed their own technology and formed unions to continue their work in the areas they occupied.

Although Hg is not allowed to be used in "garimpos", in fact amalgamation is the main process used. More than 90% of the gold present in gravity concentrates can be trapped in amalgam according to field observations at some operations. Price is not an impediment for reducing use. Even at 5 times the international price, Hg is still a cheap reagent for extracting gold, with a cost equivalent to 0.012 g of gold per tonne processed (Veiga and Fernandes, 1990). The mining and amalgamation methods used in "garimpos" are variable which, together with the fate of contaminated tailings and Au-Hg separation procedures, define the extent of Hg losses.

In excess of 2000 "garimpos" are being worked today in the Legal Amazon Region. They are responsible for the highest steel consumption per capita in South America as well as diesel oil, carpets (for gold sluices) and other goods. More than 25,000 units of mining equipment, 20 helicopters, 750 airplanes and 10,000 boats (some as large as ships) are used to produce an average of 100 tons of gold annually from the Amazon region (Feijão & Pinto, 1992).

Farid et al. (1991) evaluated a type of "garimpo" which used a grinding operation (hammer crusher) and gravity concentration (sluice or centrifuge). Figure 1 shows a simplified flowsheet of the operations involved in this type of garimpo, while an Hg-balance is provided in Figure 2. These operations are conducted on a lode ore and its weathered part. Erosion of the quartz vein hosted by ferruginous and carbonaceous phyllites spread out gold into the weathered layer. The gold grade is poorer than in quartz veins but easier to mine. Large production can be achieved, such as 3 million tonnes of run of mine/year, but gold recovery in the gravity circuit is usually lower than 50% due to poor liberation.
Concentrates are usually amalgamated in barrels or pans and the mineral portion is separated from amalgam by panning. This operation takes place either in waterboxes or in pools excavated in the ground. The method used to remove the excess mercury from amalgams is filtration using a piece of fabric to squeeze by hand. The amalgam obtained, usually with 60% gold content is retorted or simply burnt in pans. The bullion still contains 5% residual mercury which is released during melting operations in gold shops. Mercury entering the atmosphere can represent as much as 50% of that introduced into the amalgamation process when retorts are not used.

Pfeiffer and Lacerda (1988) reported that Hg losses due to dredge mining range from 30 to 45% of the Hg introduced in the process. When retorts are not used, the losses include 45% released into rivers and 55% into atmosphere.
Brazil is not a mercury producer and imports around 340 tonnes annually. From 1972 to 1984, Mexico was the main Hg supplier to Brazil. Since 1984 this picture has changed and non Hg-producing countries (the Netherlands, Germany and England) are responsible for almost 80% of the Hg entering Brazil. Mercury imports are allowed only for registered industrial uses, however the declared uses (electronic industries, chlorine plants, paints, dental, etc.) are declining. The updated Brazilian laws (Norm 434 - Aug.9/89 and Norm 14 - Jan.15/90) intend to exert more control on Hg imports. In 1989 this represented about 22% of the total 340 t of mercury. The remainder was imported for re-sale to industries, but it is estimated that over 170 t were illegally diverted to "garimpos" (Ferreira and Appel, 1991).

As a rough estimate, if we assume losses of 40% of 170 tonnes Hg, 68 tonnes/year are calculated as losses due to poorly conducted amalgamation practice. This is similar to the range of 50 to 70 tonnes Hg/year reported by Pfeiffer and Lacerda (1988). A distribution of mercury losses can be done as follows (CETEM, 1989):

- 70% by volatilization during amalgam distillation (when retorts are not used),
- 20% dragged with the amalgamation tailings and
- 10% volatilized in the gold shops when gold is melted.
CONCLUSION

The amalgamation process is reported in the American Continent since late 1840s in the California gold rush. Currently, in North America, old contaminated tailing ponds are being monitored and remedial procedures are being applied. The real extent of the mercury pollution caused by old mining activities is not clearly quantified in these regions since contribution of other modern Hg sources such as fuel combustion, chlor-alkali plants, domestic sewage, etc. was more important regionally.

This work has investigated an old mining site in Northwestern Canada (Port Douglas) in which ancient mining activities left vestiges of Hg contamination in placer deposits. The formation of natural mercury amalgam is also strongly suggested by the existence of hot springs in the region. Natural amalgam is likely formed from precipitation of Hg and Au from humic complexes in solution (dark waters). In spite of lack of bioaccumulation evidence (biota was not sampled), the high background of Hg together with high humosity of Port Douglas sediments suggest a high possibility of bioaccumulation in that mining site.

Gold mining activities in South America are reported since 1600s, however there is no new about the use of amalgamation at this time. Only in the middle of the last century, amalgamation practice was introduced as the main extractive technique for gold ores. The current gold rush, started in the early 80s in the South American Amazon is environmentally more dangerous than old timers' activities. Mercury has been extensively used causing occupational poisoning as well as contamination of the fish-eating people (Veiga and Meech, 1994). The chances to convince "garimpeiros" to convert to a mercury-free operation are not optimistic. Although most workers are aware that mercury is dangerous, they do not know how toxic it is, nor the possible consequences of releasing it into the environment. Education is one of the most important measures to help minimize mercury emission from gold mining operations in developing countries particularly in the Amazon. An intelligent approach is necessary to move "garimpeiros" toward safe working methods envisaging long term solutions and future integration of these workers into the list of legal mining companies.

REFERENCES


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