

Hg GEOCHEMICAL DYNAMICS AS A REFERENCE FOR ENVIRONMENTAL CONTROL IN GOLD MINING SITES

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ABSTRACT

This paper proposes a geochemical assessment methodology applied to the receiving environment under a historical perspective which takes into account sources and fate of mercury. It is thought to constitute a valuable tool in choosing alternatives for site rehabilitation and hazards prevention, since it reconstructs the Hg geochemical dynamics on the mine site before and after mining operations.

The elemental mercury used for amalgamating the gold particles, which is the final stage of the mineral processing, has caused abnormal Hg concentrations in waterways. This occurs principally in the amazon region, where the gold occurrences are mostly associated with alluvial deposits. The close association of these deposits with drainage waters means that the mercury lost during open-circuit amalgamation process reaches the waterways becoming prone to interactions with water and biota.

INTRODUCTION

The increasing societal demand for actions and strategies towards sustainability of small-scale gold mining in developing countries has led experts to face the challenge of managing the hazards associated with mercury pollution from active and abandoned mine sites. Mercury pollution in drainage systems and its health effects are the most frequent subjects on environmental researches dealing with small-scale gold mining worldwide. Also, filling of river beds with mineral matter originated from runoff of abandoned mining waste piles and tailings generally causes both silting of waterways and elevation of Hg concentrations in the environment.

For a better understanding of current environmental changes, namely those caused by mining operations, it is required to investigate

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the existing geochemical patterns prior to the establishment of a mining activity. The environmental history of a drainage system is commonly achieved via analyses of sediment cores taken in low-energy deposits, such as overbank and lake sediments.

The use of common geochemical and mineralogical records as indicators of Hg pollution might introduce, however, some uncertainties with regard to the partitioning of anthropogenic and lithogenic Hg, once lithogenic Hg concentrations in sediments may range from 0.05 to 0.30 µg/g according to the mineralogy found within catchment soils (Rodrigues-Filho and Müller, 1999).

Based on observations from temperate regions, several authors pointed out that definitive evidence for soil erosion may be difficult to obtain from sediment chemistry because changes in soil mineralogy are too subtle to detect (Engstrom and Wright Jr., 1984; Chesworth, 1972). However, this seems not to be the case in tropical regions, where chemical weathering causes marked mineral transformations and the relative accumulation of less mobile metals in surface horizons under neutral or oxidizing conditions, such as Al, Ti, Fe, Mn, Be, Ti, Cr and Ni. Thus, geochemical contrasts among soil horizons favor the reconnaissance of source imprints in sediments (Wasserman, Silva-Filho and Villas Bôas, 1998).

Mineralogy of tropical soils also helps a great deal in identifying sediment provenance, since contrasting accumulation of quartz and secondary minerals within weathering profiles is a well documented fact (Lucas et al., 1993; Kopp, 1986; Irion, 1984; Curi and Franzmeier, 1984). Goethite and gibbsite generally occur in the uppermost soil horizon as a result of hydration of hematite and leaching of silica from kaolinite, respectively (Nahon, 1986).

SOURCES OF Hg IN THE BRAZILIAN AMAZON

Estimates of total gold production from small-scale gold mining (*garimpos*) in the Amazon account 60-70 t/a from 1980 to 1990, while almost 50% of that were due to the production from the Tapajós region, state of Pará (SEICOM, 1992). During the 90's, garimpo gold fields experienced a decline period mainly due to lowering of the ratio gold price/production cost.

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A ratio produced-Au/released-Hg of 1.4 has been calculated for the gold fields in Alta Floresta, state of Mato Grosso, where processing technology usually consists of concentration through sluice and amalgamation as a separate process (CETEM, 1992). This Au/Hg ratio, however, is much higher in those sites where concentration and amalgamation are carried out together using copper plates into the sluice. This practice has been reported in many garimpos of the Tapajós region (SEICOM, 1992). Thus, a reasonable estimate of the Hg load released to the Brazilian Amazon due to gold mining for the last 20 years accounts more than 1000 tonnes.

Another source of Hg in the Amazon is the atmospheric Hg released from deforestation, evapo-transpiration of leaves, vegetation decay and global volcanic activity. Among these sources deforestation is likely to contribute with a significant load, which has been estimated from the biomass distribution in the Amazon as 710 tonnes for the last 20 years (Veiga et al., 1994).

The following three major Hg sources are pointed out for the Brazilian Amazon, while four different types of gold fields are classified according to the technology employed, proximity to waterways and awareness of miners, which are indicative of distinct polluting potentials (Table 1) :

1. Small-Scale Gold Mining (*garimpos de ouro*)
 - Gold fields of active alluvial deposits – explored by rafts (*garimpo de balsa*) ;
 - Gold fields of inactive alluvial deposits – explored by hydraulic jet (*garimpo de baixão*);
 - Gold fields of lateritic deposits – explored through open pit (*garimpo de sequeiro*);
 - Gold fields of primary deposits – explored through open pit or shaft (*garimpo de filão*);
2. Deforestation and vegetation decay;
3. Naturally Hg-enriched soils through long-term atmospheric precipitation.

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Table 1 – Polluting potential of different gold fields in the Brazilian Amazon

Type of Gold Field	Hg-containing waste	Atmospheric emission	Silting of drainage	Nomadic character
Raft - alluvial	High	High	High	High
Hydraulic jet - alluvial	High	High	High	High
Lateritic Au	Moderate	Moderate	Moderate	Low
Primary Au	Moderate	Moderate	Low	Low

Naturally Hg-enriched soils are simultaneously source of Hg to drainage systems and fate of long-term atmospheric Hg precipitation. A previous study assessing mercury pollution in two gold mining regions of the Brazilian Amazon has shown that Fe-rich soils and sediments play a major role in retaining/transporting Hg (Rodrigues-Filho and Maddock, 1997). There, a possible association between Hg and Al hydroxide was not taken into consideration.

Similarly, Roulet et al. (1996) have observed a marked accumulation of Hg in surface horizons of different Amazonian soils, averaging 0.20 µg/g. The authors pointed out that these Hg levels are one order of magnitude higher than those reported for temperate soils. Furthermore, Hg accumulation appeared to be entirely controlled by Fe and Al hydroxides. The closely associated contents of Fe and Al oxyhydroxides did not allow the authors to evaluate whether Hg is enriched on Fe or Al oxyhydroxides, or both.

A study on Hg dynamics from soils and lake sediments was carried in Lake Silvana, state of Minas Gerais (Rodrigues-Filho and Müller, 1999). There, a widespread Hg accumulation in surface horizons of lateritic soils is likely to be mainly controlled by adsorption onto gibbsite (Al (OH)₃). Hg concentrations in B horizons reach up to 0.28 µg/g and represent an increase to values 10 times higher than those observed in the lowermost horizons. Hg in surface soils is likely to be adsorbed onto gibbsite, since a positive correlation ($r = 0.83$) exists between Hg and *aqua-regia* soluble Al within soil profiles (Fig. 1).

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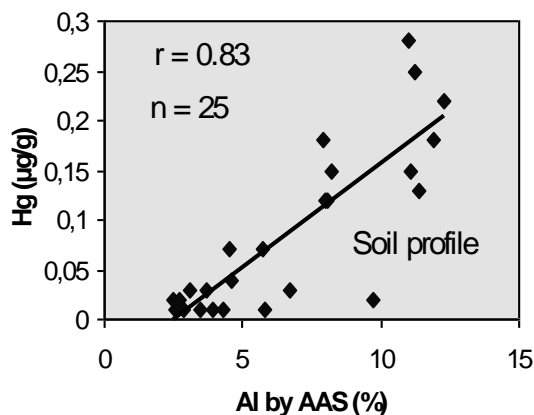


Figure 1. Correlation between Hg and *aqua-regia* soluble Al in soil profiles – Lake Silvana catchment.

It is noteworthy that a presumable Hg immobility during weathering, as indicated by its accumulation in surface soil horizons, is not in accordance with its ionic potential which points to its high mobility. Metallic Hg (Hg^0) seems to be easily oxidized to inorganic salts, notably halides and sulfates, as a result of natural leaching or weathering cycles (Jonasson and Boyle, 1979). Based on data from Canadian soils, these authors have demonstrated that Hg concentrations tend to be enriched in surficial humic soils, presumably due to vegetation decay, but with enrichment factors relative to the saprolite not greater than 2. There, concentrations in the B horizon exhibit no enrichment relative to the saprolite horizon.

As tropical ferralitic soils are thought to be as old as ~ 5 Ma. (Nahon, 1986; McFarlane, 1983), the long-term deposition of atmospheric Hg in soils rich in Fe and Al hydroxides is likely to explain the widespread Hg accumulation in surficial ferralitic soils rather than a weathering-driven accumulation process from the parent rock. Therefore, most of the Hg found in surficial tropical soils is likely to be derived from natural rather than anthropogenic sources, as sediments with elevated Hg concentrations have been deposited in Lake Silvana since 9000 yr ago, according to radiocarbon age determinations (Fig. 2) (Rodrigues-Filho and Müller, 1999).

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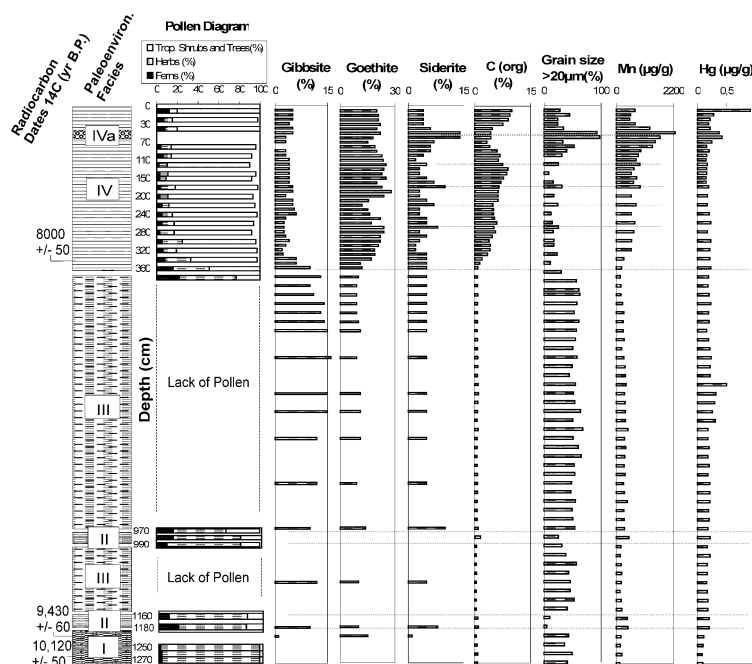


Figure 2. Summary diagram of sedimentary data - pollen, mineral and metal - Lake Silvana

FATE OF Hg IN TWO GOLD MINING AREAS OF THE BRAZILIAN AMAZON

The municipality of Pocone is located at the northern edge of the Pantanal wetland, state of Mato Grosso, an important ecological unit for conservation, where savannah-like vegetation covers yellow-red latosols. Most of the gold occurs as nuggets associated with lateritic soils.

The municipality of Alta Floresta is located at the northern part of the state of Mato Grosso, where the terrains are covered by typical Amazon rain forest. Most of the gold occurrences are associated with alluvial deposits, although more recently primary Au occurrences have

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been prospected. Also in the region of the Tapajos river, prospection of primary Au occurrences has been observed.

Sampling campaign was designed to cover areas where different variables could affect Hg concentration in sediments and soils – namely rocky substrate, characteristics of drainage waters, vegetation, pedological horizons (soils) and proximity to the gold fields (Rodrigues-Filho and Maddock, 1997). “Geoaccumulation indexes” (Igeo) of Hg in sediments were used to assess pollution levels in the aquatic environment (Müller, 1979). The “Igeo” is defined as follows:

$$I_{geo} = \log_2(C_n/1.5.B_n)$$

where, C_n is the measured Hg concentration in the fraction < 2 μm (clay), and B_n is the background value of Hg found in sub-recent clayey sediments.

Hence the “Igeo” in class 0 indicates absence of contamination, and the “Igeo” in class 6 represents the upper limit of maximum contamination. The Igeo can also be applied to the grain size fraction < 74 μm used in this study provided there is definition of background values in this fraction.

An average Hg concentration of 0.10 $\mu\text{g/g}$ was found based on stations with no impacts of gold mining. This Hg background in the < 74 μm fraction of fluvial sediments was higher than that in lacustrine sediments in remote areas of the Pantanal wetlands, with 0.02 $\mu\text{g/g}$ (Lacerda et al., 1991). This lower value in lacustrine sediments is probably due to the distance from the lithogenic sources of Hg and to the extremely low sediment transportation energy of the waters throughout the Pantanal lowlands.

The Bento Gomes River is the depository of sediments transported by tributary drainage waters and was the main focus of study in the Pocone area.. At the sampling point where the river forms a large lake, high concentrations of Hg (class 3) and other trace metals were observed in sediments, denoting this lake as a sink for metals. Downstream of the lake, Hg concentrations in sediments were considerably reduced and come close to background levels.

In the Alta Floresta region, the close association of alluvial Au deposits with the waterways has caused higher Hg concentrations in sediments than those observed in the Pocone region. There was a

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clear predominance of Hg associated with the grain size fraction < 74 µm downstream of the main Hg sources in the Teles Pires River. Near the main sources there was a predominance of Hg in coarser grain size fractions > 74 µm, indicating that the Hg is found principally in the elemental form and is not prone to interactive processes with sediment particles. Nevertheless, Hg concentrations detected in sediments of the Tele Pires River close to the *garimpos* were the highest of the area studied, reaching an Igeo class 5 or “highly polluted”.

Sampling at Alta Floresta was also meant to assess the dispersion of Hg released during amalgam burning by the gold-buying shops in the urban area. A total of 130 surface soil samples were collected from a regular sampling grid of approximately 100 x 300 m, covering an area of about 3.4 km².

Mercury concentrations in the surface soils were clearly predominated by abnormal values related to Hg emission from gold-buying shops. Superficial contamination of the soils occurs primarily in the vicinity of the sources which indicates that some of the vaporized Hg is quickly deposited. High anomalies (> 1.0 µg/g) were observed at up to 600 m distant from the sources while less pronounced anomalies (0.2 – 0.3 µg/g) were found up to 1000 m away. Dispersion of Hg in the soils follows two directions: east and southwest. These directions coincide with those for winds in the rainy season and confirms that rain is principally responsible for the short-term deposition of vaporized Hg.

One sediment core was also taken in a lake located in the vicinity of Alta Floresta, which formed after the construction of a road in 1978. The sediment core was composed of red clayey sediments and organic matter in the first 10 cm, and a white gley between 10 and 40 cm. Mercury concentrations show background values of 50 to 70 µg/g in the lowest 30 cm section and a significant increase in the first 10 cm, reaching up to 210 µg/g. It has been assumed that the marked change of the sediment composition at 10 cm of depth was caused by the formation of the lake itself in 1978. Hence, the Hg flux into the lake was calculated by subtracting the obtained background concentration from the measured concentration for each core section, according to the following expression (Cundy and Croudace, 1995):

$$f(\text{Hg}) = \beta \cdot (C_i - C_0) \cdot s \cdot 10^4$$

where,

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$f(\text{Hg}) = \text{Hg flux } (\mu\text{g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1})$

$\rho = \text{sediment density } (\text{g}\cdot\text{cm}^{-3})$

$C_i = \text{Hg concentration at a } i \text{ depth } (\mu\text{g}\cdot\text{kg}^{-1})$

$C_0 = \text{background concentration } (\mu\text{g}\cdot\text{kg}^{-1})$

$s = \text{sedimentation rate } (\text{cm}\cdot\text{yr}^{-1})$

The distribution of Hg flux into this lacustrine environment from 1976 to 1996 has been calculated and compared with the gold production from the Alta Floresta region, whose data have been reported by Hacon (1996). Both gold production and Hg flux are positively correlated, indicating that amalgam burning contributes to increase Hg concentrations in lacustrine sediments (Fig. 3). This indication constitutes a major environmental concern, since lakes play an important role in the biogeochemical cycle of Hg. Rather than sinks, lakes are like reactors capable of changing inorganic Hg into ready bioavailable organic chemical forms.

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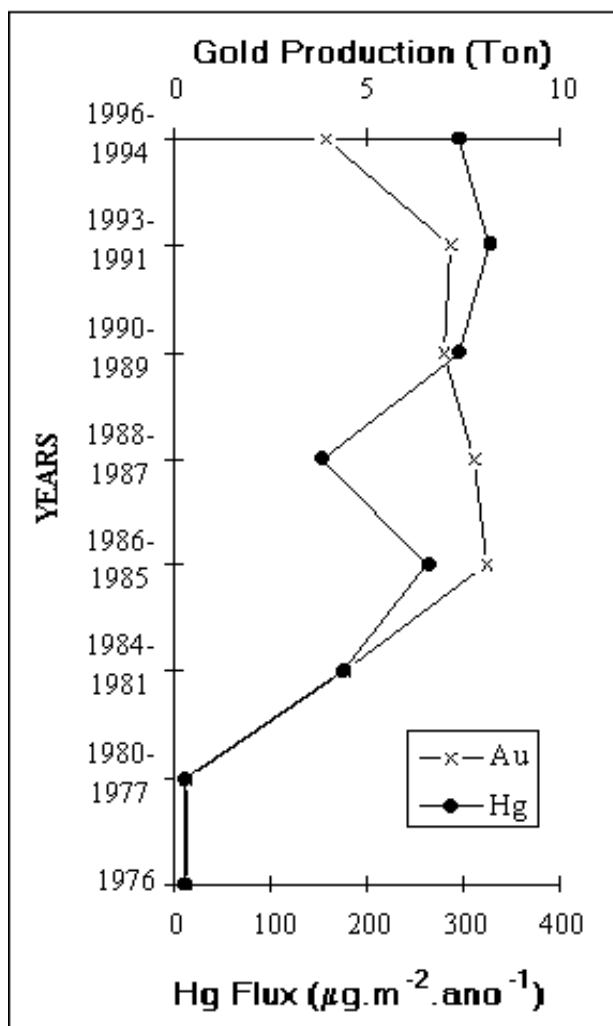


Figure 3. Gold production from Alta Floresta and mercury flux into the lake studied.

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RECOMENDATIONS FOR DESIGNING A WORKING PLAN TOWARDS ENVIRONMENTAL CONTROL IN GOLD MINING SITES

1. Mercury geochemical dynamics:
 - Assessment of local Hg sources and their effects upon the aquatic environment;
 - Risk analysis using fishes as bioindicators;
 - Indication of hot spots of Hg pollution in waterways and tracing of Hg pathways through the food chain to human populations.
2. Mineral processing:
 - Development of new technologies and adaptation of existing ones towards prevention and abatement of Hg pollution derived from small-scale gold mining;
 - *In situ* demonstration to local miners and stakeholders of the economic and environmental benefits derived from the technological improvements.

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