

## 9 Impact of Gold Mining on Mercury Contamination and Soil Degradation in Amazonian Ecosystems of French Guiana

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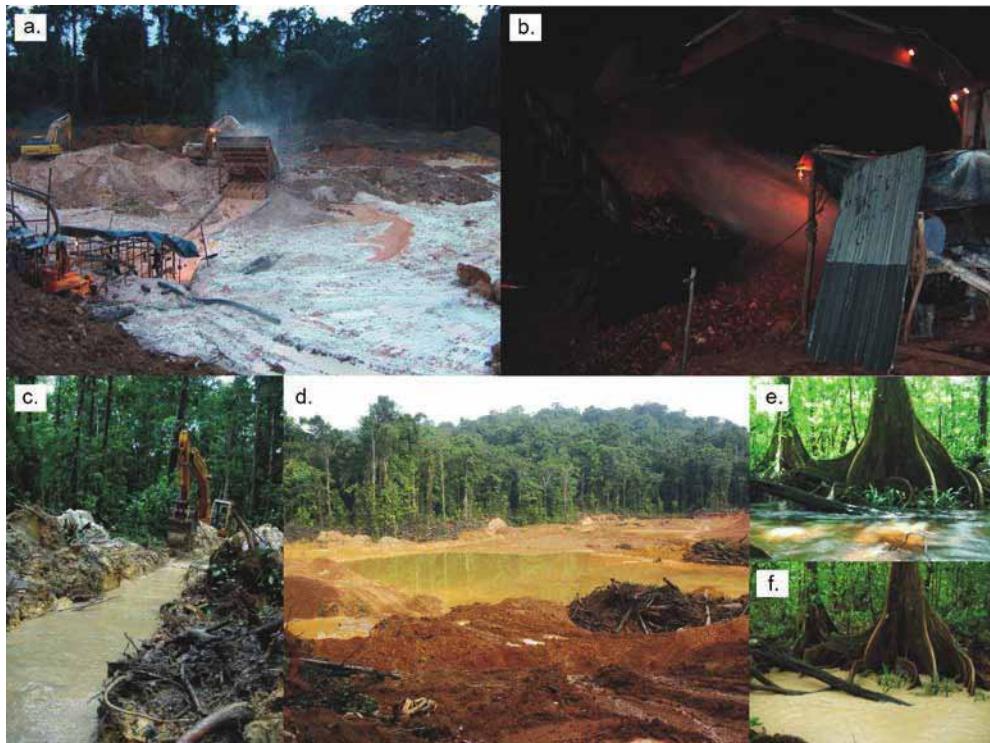
### 9.1 Introduction

As early as the 16th century, major expeditions were searching for gold and other precious metals and ores in the ‘New World’ (Nriagu, 1994; Tandeter, 2006). Later, in the middle of the 19th century, gold rushes that started in California spread to South America, as well as Australia and South Africa (Nriagu, 1994; Ali, 2006). Their main goal was to extract alluvial gold, occurring as fine particles in sediments derived from soils and weathered rocks. Another more current strategy of artisanal mining groups is to extract eluvial gold concentrated in the soil as fine particles and nuggets, originating from the *in situ* weathering of rocks. The extent of such artisanal small-scale gold mining (ASGM) activities varies with the price of gold (Malm, 1998). According to the United Nations Industrial Development Organization, 10–15 million people worked on ASGM sites throughout the world in 2004 (Veiga and Baker, 2004) in more than 160 mainly developing countries (Telmer and Veiga, 2009). Unfortunately, there is little information about the size and type of ASGM operations (Telmer and Veiga, 2009) or the surface area of soil and sediment worked;

thus, the exact spatial extent and magnitude of impacts are difficult to determine.

Gold mining changes land use drastically, with a considerable impact on the entire ecosystem, including soil. First, extracting eluvial deposits requires removing vegetation and then using powerful water jets to strip off surface soil horizons and reach the gold-bearing layer (Fig. 9.1). Besides the large loss of topsoil, these practices affect the turbidity of watercourses (Fig. 9.1) and sometimes their drainage patterns (Telmer *et al.*, 2006; Hammond *et al.*, 2007) and thus have impacts far beyond the local site of operation. Second, fine gold particles in sediments and soils are recovered by amalgamating them with mercury (Hg) (Nriagu, 1994; Malm, 1998), which is subsequently burnt to evaporate the Hg. The amalgamation process releases 650–1350 t Hg into the global environment annually (mean annual release of 1000 t, of which 350 t are emitted to the atmosphere through burning of amalgam and 650 t are discharged into the hydrosphere as elemental and particulate Hg (Telmer and Veiga, 2009). Mercury contamination of aquatic trophic chains is the most alarming health risk for local populations, whose protein diet is largely provided by carnivorous fish and

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**Fig. 9.1.** Illustration of artisanal or semi-industrial gold mining activities in French Guiana. From top left to bottom right: (a) mechanical removal of surface soil horizons, (b) stripping off of gold-bearing material with water jets to recover gold particles and nuggets, (c) digging of a derivation canal, (d) settling basin, and water turbidity in Combat Creek (e) before and (f) during artisanal small-scale gold mining activities.

their predators (Lebel *et al.*, 1996, 1997; Fréry *et al.*, 2001; Laffont *et al.*, 2011). These top-chain predators concentrate Hg in its most toxic and bio-accumulative form, monomethyl-Hg (Agaki *et al.*, 1995; Mason *et al.*, 1995; Barbosa *et al.*, 2003; Coquery *et al.*, 2003).

In this chapter, we focus on the impact of ASGM on the Hg contamination of tropical soils, with special attention on how the change in land use (i.e. gold extraction practices) alters the soil processes that affect Hg fate and behaviour. We explain the soil formation and transformation processes that determine the accumulation or mobilization of Hg, reflecting the dual role of soils as both 'sink' and 'source' of Hg. First, we compare the fate and behaviour of Hg from ASGM with that from the natural geochemical background, considering the nature and abundance of carrier phases and soil functioning. Second, we describe how former and

current ASGM activities intensify the soil processes that favour Hg mobilization by surface and near-surface runoff to watercourses, Hg emission to the atmosphere and production of monomethyl-Hg.

This chapter combines research carried out in French Guiana, a territory located in northern South America (Tessier *et al.*, 2003; Grimaldi *et al.*, 2004, 2008; Guédron *et al.*, 2006, 2009, 2011a,b), with studies from Brazilian Amazonia. French Guiana, like much of Amazonia, is greatly impacted by ancient and current, legal and illegal ASGM activities. The impact on tropical soils, as well as on ecosystems as a whole, has been well studied in these areas. Furthermore, as the environmental legislation in force since 2006 in French Guiana prohibits the use of Hg at gold mining sites, it is relevant to compare ASGM with or without the amalgamation practice. For a better understanding of the

soil processes involved, the main research issue is to promote mining practices that can reduce health and environmental risks.

## 9.2 Origins and Carrier Phases of Mercury Accumulated in Soils

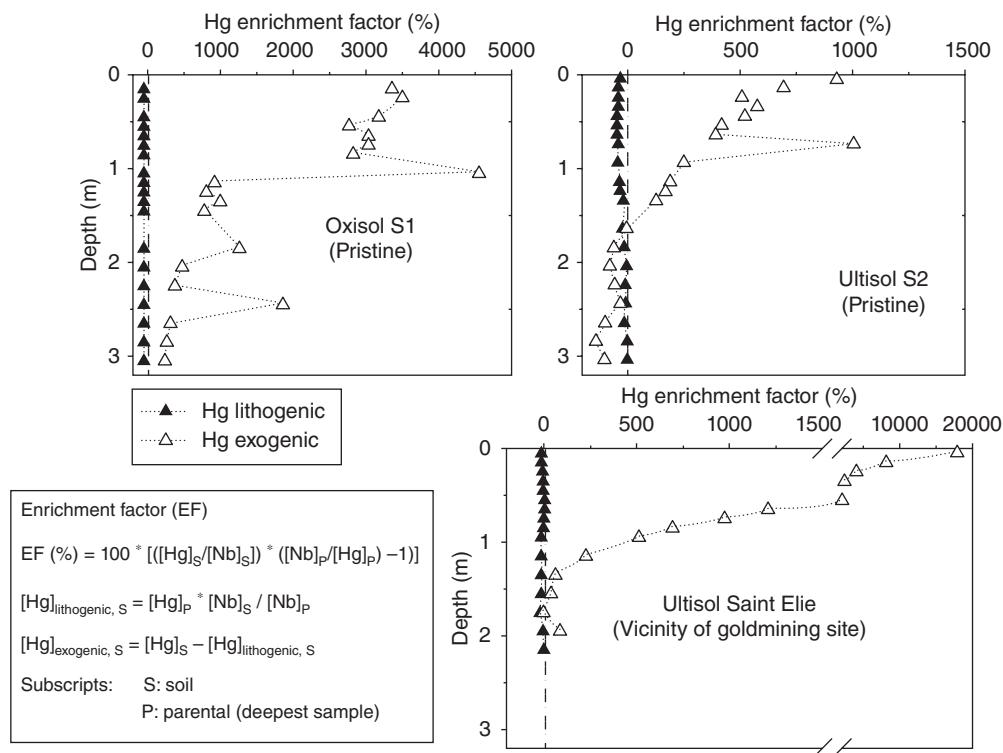
Mercury inputs from ASGM activities add to Hg already accumulated in the soil from two distinct origins: (i) weathering of parent rocks (lithogenic Hg); and (ii) atmospheric deposition derived from degassing of the Earth's crust and oceans, along with long-term human activities since the industrial era.

The magmatic and metamorphic rocks making up the Guiana and Brazilian shields, which border the Amazon basin to the north-east and south, have low concentrations of Hg, ranging from 4 to 7 ng g<sup>-1</sup> for granites, basalts and andesites in French Guiana (Guédron *et al.*, 2006). These concentrations are lower than, or equal to, those obtained for rocks of a comparable nature found in Brazil (Fiorentino *et al.*, 2011) and on other continents (Gao *et al.*, 1998). Except for certain minerals, which are generally sulfur (S)-bearing (cinnabar: HgS), Mercury is present as impurities in the crystalline lattices of minerals (Andersson, 1979). Weathered materials (alterites) have higher Hg concentrations than parent rocks. The weathering zone is often 20–40 m thick in humid tropical regions where rock exposures are limited to inselbergs. Analysis of several alterites derived from the same parent rock shows that the Hg concentration increases progressively with the degree of weathering, up to approximately 50 ng g<sup>-1</sup> (Oliveira *et al.*, 2001; Guédron *et al.*, 2006). Mercury concentrations in alterites are themselves lower than those from the soil horizons above them, in particular the clayey and micro-aggregated Oxisol horizons that are a few metres thick. The Hg concentration in Oxisols can reach 800 ng g<sup>-1</sup> in the fine fraction (<2 mm) and sometimes more than 1 µg g<sup>-1</sup> in the ferruginous coarse fraction (>2 mm), which often represents more than half of the bulk soil fraction (Oliveira *et al.*, 2001; Grimaldi *et al.*, 2008).

The strong contrast between the parent material and the Oxisols can be explained by the

long period of intense weathering under a hot and humid climate. During weathering, Hg can concentrate in Oxisols, along with elements such as iron (Fe), aluminium (Al), manganese and titanium, while other elements, including calcium, magnesium and silica, are more mobile (Nahon, 1991). The proportion of lithogenic Hg has been estimated using refractory elements (Fe, niobium, uranium and zinc), which are known to be relatively immobile, not derived from an atmospheric source, and are indicators of the degree of weathering (Oliveira *et al.*, 2001). It appears that rocks are of minor importance as a source of Hg (in French Guiana, 10–25% of total Hg depending on soil type) compared to long-term natural atmospheric deposition and anthropogenic inputs (Guédron *et al.*, 2006; Grimaldi *et al.*, 2008) (Fig. 9.2). The contribution of anthropogenic Hg increases even more near gold mining sites using amalgamation, where the total Hg concentrations in the soil can reach several micrograms per gram locally (Guédron *et al.*, 2006, 2009).

While most of the Hg accumulated in soils is not derived from their parent rocks, these materials have an indirect influence on the Hg enrichment, from natural or anthropogenic sources, due to the nature and abundance of secondary minerals produced by weathering, which are likely to fix Hg. The Hg carrier phases identified in Amazonian soils by selective extraction methods (Kostka and Luther, 1994; Bloom *et al.*, 2003) are: (i) organic matter; and (ii) amorphous and crystallized Fe-oxides (Al-substituted goethite and haematite), both in the fine fraction (<2 mm) and in ferruginous nodules (Roulet and Lucotte, 1995; Roulet *et al.*, 1998; Guédron *et al.*, 2009). Hg has a strong affinity for the S groups of organic molecules (Schuster, 1991; Skyllberg *et al.*, 2000; Manceau and Nagy, 2008), which explains its commonly observed correlation with S and organic carbon (C) (Guédron *et al.*, 2009). Owing to the rapid mineralization of organic matter in Oxisols, oxy(hydr)oxides (whether associated with residual organic matter or not) take over in importance for Hg retention. The ability of Fe-oxides to retain Hg in its divalent form (Hg<sup>2+</sup>) is even higher when these oxides are amorphous or poorly crystallized, because of their large surface area and the atomic ordering defects induced by a high rate of substitution of



**Fig. 9.2.** Lithogenic and exogenic mercury (Hg) enrichment factors (%) in pristine Oxisol and Ultisol from the Leblond toposequence (upper panel) and in an Ultisol sampled near the Saint Elie goldmine camp (French Guiana). Niobium (Nb) was selected as an immobile element, uranium (U) as proxy for Hg behaviour during weathering and pedogenesis, and the mean composition of the three lowermost samples of both Ultisols' alterite as reference material. (Modified from Guédron et al., 2006.)

Fe by Al (Schwertmann and Latham, 1986; Schwertmann and Cornell, 2000). These various organic and mineral phases are associated with kaolinite, forming clayey micro-aggregates in the upper soil horizons (Tandy *et al.*, 1990), so that the abundance of clay particles (<2 µm fraction) accounts for the Hg content of the soil, in the same geological setting. Highly clayey Oxisols developed on sedimentary formations of the central Amazonian basin (Roulet *et al.*, 1998) have lower Hg concentrations (<200 ng g<sup>-1</sup>) than Oxisols on the Guiana Shield (350–810 ng g<sup>-1</sup> – Richard *et al.*, 2000; Guédron *et al.*, 2006, 2009; Grimaldi *et al.*, 2008) and Brazilian Shield (80–640 ng g<sup>-1</sup> – Oliveira *et al.*, 2001). Indeed, the Oxisols of the central Amazonian basin are richer in clay but poorer in oxides, which is an indirect result of the nature of their parent rocks.

### 9.3 Soil Processes Controlling Mercury Concentrations in Soils

Soil processes influence the fate of Hg not only by determining the nature and abundance of carrier phases, but also more directly by controlling hydric and biological soil functioning, which affect Hg speciation and migration. There is a high degree of pedological diversity in Amazonia (composition and functioning) across a wide range of geological formations and climatic conditions at the regional scale (Richter and Babbar, 1991; Quesada *et al.*, 2011). Even at the local scale, soils formed from the same bedrock can display distinctively different properties (Chauvel *et al.*, 1987; Boulet *et al.*, 1993). As a consequence, away from gold mining sites the pedological diversity associated with past and present

soil formation processes explains the spatial variability of Hg content observed for the same parent rock and under the same conditions of atmospheric input (Roulet *et al.*, 1998; Oliveira *et al.*, 2001; do Valle *et al.*, 2005; Guédron *et al.*, 2006; Grimaldi *et al.*, 2008).

This pedological diversity results from the transformation of Oxisols by two active natural processes (i.e. erosion and hydromorphy) under present-day tectonic and climatic conditions. First, erosion, diffuse under forest cover, produces a gradual thinning of the soil, bringing poorly structured and more impermeable alterites closer to the surface, thus leading to the development of Ultisols that are superficially depleted in clay by dissolution and eluviation (Grimaldi *et al.*, 2004). Second, hydromorphy is favoured by the presence of these alterites near the surface on slight slopes, where vertical or lateral water drainage is limited. Therefore, under long-lasting conditions of excess water, this process results in the chemical and physical degradation of the soil (depletion of Fe and clay; disappearance of micro-aggregated structure).

The micro-aggregated structure of Oxisols, well developed in thicknesses varying from one to a few metres, leads to an effective porosity that facilitates water and gas transfers; thus, water drainage is primarily vertical and occurs under oxidizing conditions. The high Hg content of Oxisols, sometimes down to a depth of 3 m, can be explained by the abundance of carrier phases, as well as by water transfer and biological activity, which redistribute Hg of atmospheric origin in the soil profile (Guédron *et al.*, 2006; Grimaldi *et al.*, 2008) (Fig. 9.3). The Hg can migrate with other substances transported by water, in particular organo-mineral complexes such as fulvic acids associated with Fe and Al (Ravichandran, 2004). Bioturbation of the soil, i.e. structural rearrangement of soil particles by invertebrates such as termites, worms and ants, is active in Oxisols, also contributing to the penetration of particulate-bound Hg deep into the soil, while ensuring aggregation of the soil and thus maintaining its permeability (Lavelle *et al.*, 2006).

In contrast, in the Ultisols, drainage during heavy rains is essentially lateral and superficial, due to the presence of alterites at depths of less than 1 m (Molicova *et al.*, 1997; Grimaldi *et al.*, 2004). The Hg carrier phases become less abundant in the surface layers of the Ultisols due to

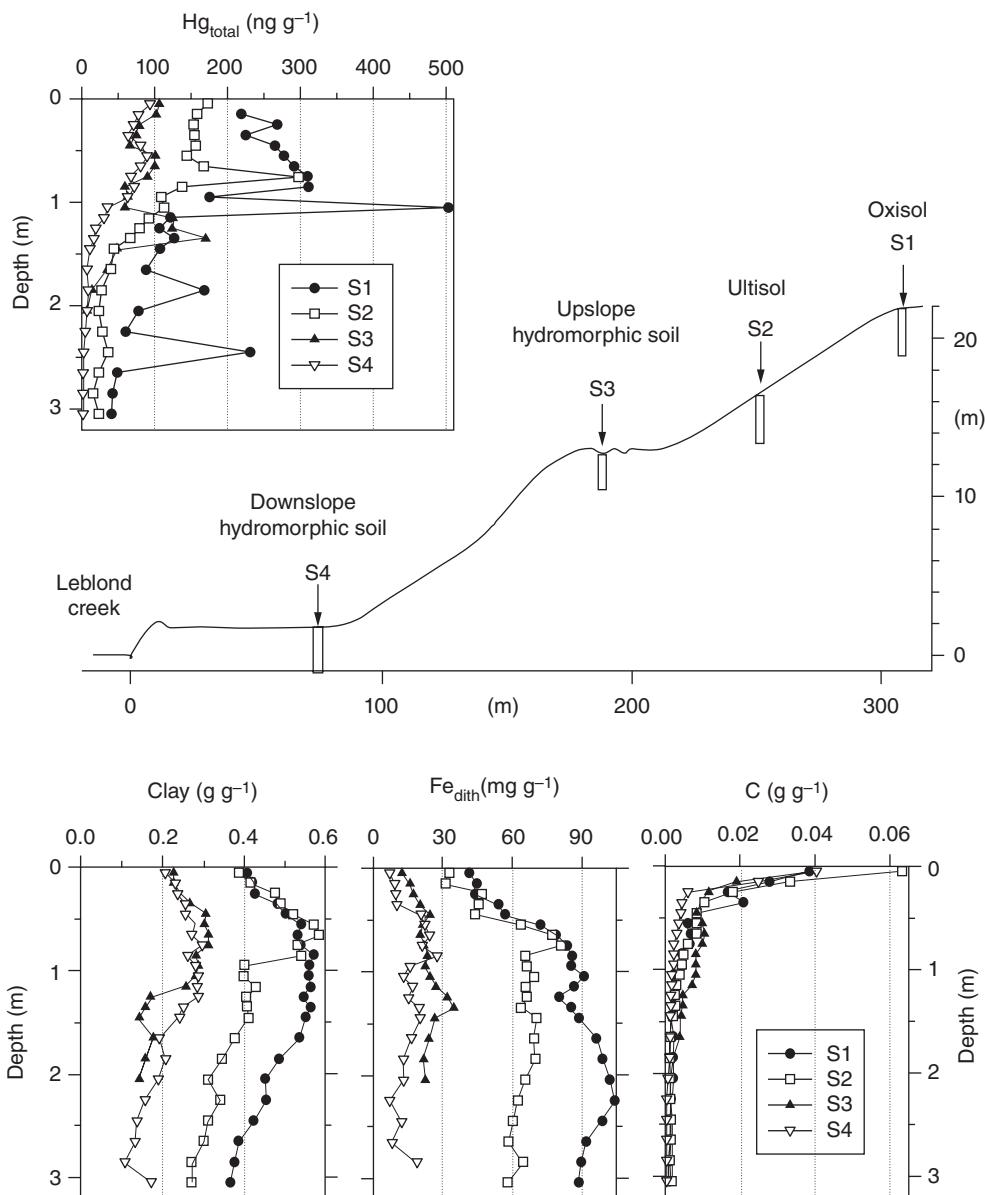
frequent water excess and reducing conditions (Guédron *et al.*, 2006; Grimaldi *et al.*, 2008) (Fig. 9.3). Moreover, the poorly structured alterites are depleted in Hg, which is primarily lithogenic and preferentially integrated into the lattice of crystallized Al- and Fe-oxides (Guédron *et al.*, 2009).

Hydromorphic soils are characterized by poor water drainage and reducing conditions (do Nascimento *et al.*, 2004; Fritsch *et al.*, 2006). These soils are located in areas of slight or flat slopes of the watershed and in depressions close to the riverbed, and are sometimes developed on summit shoulders or mid-hillslope areas that are hydrologically more isolated (Fig. 9.3). In the hydromorphic soils, reducing conditions favour dissolution of amorphous and crystallized Fe-oxides (Patel-Sorrentino *et al.*, 2007), as well as emission of elemental gaseous Hg into the atmosphere by reduction of its ionic divalent species (Tessier *et al.*, 2003). Consequently, the two natural processes of transformation of Oxisols into Ultisols and hydromorphic soils lead to a redistribution of natural or anthropogenic Hg in the soil or, more often, to its export, as discussed later.

#### 9.4 Relative Importance of Mercury Anthropogenic Inputs versus Geochemical Background

The last great gold rush in Amazonia released approximately 2000 t Hg into the environment (Malm, 1998), reaching 200 t year<sup>-1</sup> in Brazil during the 1980s, of which 60% was released into the atmosphere due to burning of gold-Hg amalgams (Lacerda and Salomons, 1998). Among other human activities, burning associated with Amazonian deforestation also releases considerable quantities of Hg: 6–9 t year<sup>-1</sup> (Roulet *et al.*, 1998).

Consequently, Hg fluxes reaching the soil via direct wet and dry atmospheric deposition (above the forest canopy) were estimated at 151 µg m<sup>-2</sup> year<sup>-1</sup> at less than 10 km from a mining site in Brazil (Tumpling *et al.*, 1996), decreasing rapidly with distance to 18–25 µg m<sup>-2</sup> year<sup>-1</sup> at 100 km (Fostier *et al.*, 2000; Fadini and Jardim, 2001). At this distance, the contribution of gold mining to wet atmospheric fall out was estimated at 7–17 µg m<sup>-2</sup> year<sup>-1</sup>. Hg stocks were evaluated at 0.65 and 2 g m<sup>-2</sup> in the uppermost



**Fig. 9.3.** Total mercury ( $Hg_{total}$ ), clay, crystalline iron extracted with dithionite ( $Fe_{dith}$ ) and total carbon (C) contents in four soil profiles (S1–S4) of the pristine Leblond toposequence (French Guiana). (Modified from Guédron *et al.*, 2006 and unpublished data.)

2 m of two Oxisols of French Guiana, respectively, without including the Hg accumulated in ferruginous nodules (Guédron *et al.*, 2009). A Hg flux of  $17 \mu\text{g m}^{-2} \text{ year}^{-1}$  over the last 150 years would have supplied  $2.6 \text{ mg m}^{-2}$ , that is to say, only 0.39 and 0.13% of the Hg stock,

respectively, in both Oxisols. In the hydromorphic soils, which are markedly less rich in Hg, the same Hg flux would account for 1.7% of a stock of  $0.15 \text{ g m}^{-2}$ . These calculations do not take into account dry atmospheric deposition ( $Hg^{2+}$  bound to aerosols as well as elemental  $Hg^0$ ),

which, in forests, is adsorbed on to the leaves of the canopy before being washed off by rains or reaching the ground with the fall of leaf litter (Fostier *et al.*, 2000; Mélières *et al.*, 2003; Guédron *et al.*, 2013). Mining activities at the beginning of the European colonization of South America, before the 150 years assumed here for calculating fluxes, released large quantities of Hg (Nriagu, 1993, 1994), which could also contribute to the Hg stock in the soils. Despite these approximations, it appears that anthropogenic activities, in particular gold mining, only make a minor contribution to the Hg stock of soils compared to other natural atmospheric sources over long periods. Away from gold mining sites, the geochemical background of Hg is thus predominant in controlling its content in Amazonian soils.

However, Hg pollution is clearly apparent in soils intensely reworked by gold prospecting activities. The Hg concentrations at such sites are an order of magnitude higher, on average, than those from pristine soils, irrespective of their texture (Guédron *et al.*, 2009) (Fig. 9.2). Their spatial variability over short distances is high (Guédron *et al.*, 2009). Exceptionally high concentrations were observed in an undisturbed soil of a gold mining camp, probably caused by the input of  $Hg^0$  in liquid (waste or accidental pollution) and gaseous phases (amalgam burning) (Guédron *et al.*, 2006). It is thus noteworthy that a major proportion of Hg is present in the form of isolated droplets of elemental Hg ( $Hg^0$ ), quantifiable by pyrolysis (Bollen *et al.*, 2008) that are sometimes amalgamated with particles of gold (Guédron *et al.*, 2009).

## 9.5 Mobilization of Mercury from Soils

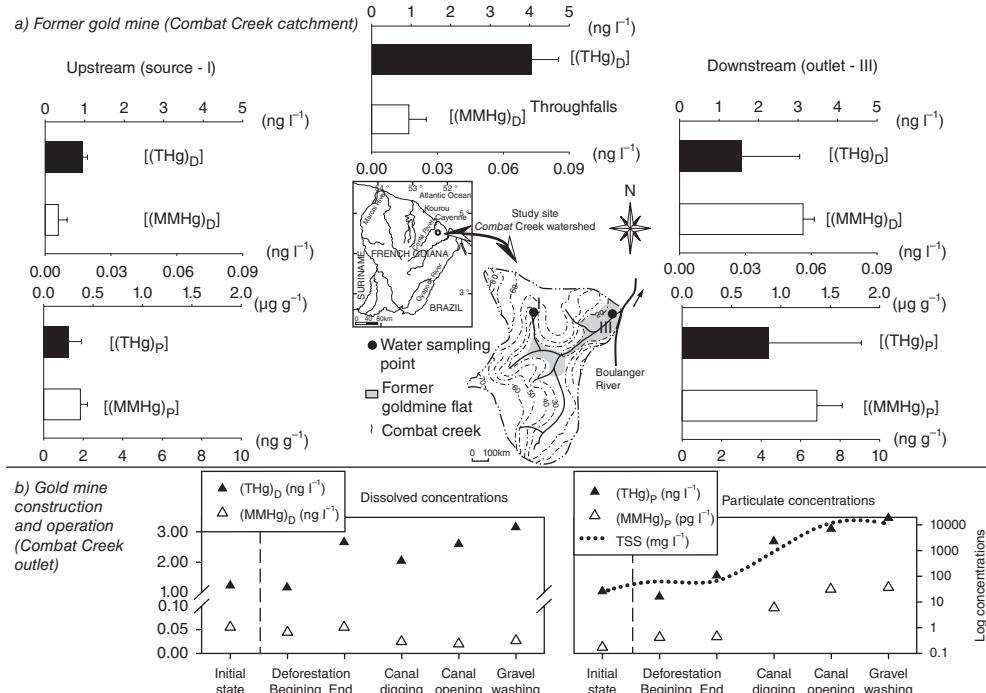
Natural or anthropogenic Hg stored in soil can be mobilized by water fluxes on the surface and in the soil, or emitted to the atmosphere. In Amazonia, intense rain events play a major role in leaching Hg from the atmosphere and the canopy to the soil and watercourses. Mercury is mobilized in its various chemical forms, either dissolved or associated with solid suspended particles. In streams draining Oxisols, concentrations of dissolved total Hg are lower (around  $1\text{ ng l}^{-1}$ ) than

in both rainwater and throughfall ( $4\text{ ng l}^{-1}$ ), confirming the role played by Oxisols as a sink for Hg (Guédron *et al.*, 2011a) (Fig. 9.4a). In contrast, surface runoff and the temporary near-surface groundwater formed during strong rainfalls in the Ultisols mobilize Hg, both associated with particles and in soluble form. A large part of the mobilized Hg is in particulate form during the peaks of discharge, while the proportion of dissolved Hg tends to increase during the discharge recession (Tessier *et al.*, 2003; Guédron *et al.*, 2011a). Due to the considerable soil erosion produced by ASGM practices, particulate Hg fluxes into streams include not only anthropogenic Hg but also long-term accumulated Hg from the natural background.

Long-lasting water saturation in hydro-morphic soils after intense rainfall favours the reduction of  $Hg^{2+}$  and its emission into the atmosphere as a gaseous phase. This other mechanism for the mobilization of Hg in the soil was demonstrated by experiments in the laboratory and in the field (Tessier *et al.*, 2003; Peretyazhko *et al.*, 2006). The concentrations of gaseous elemental Hg in the atmosphere range from  $2\text{--}9\text{ ng m}^{-3}$  above well-drained soils and from  $14\text{--}95\text{ ng m}^{-3}$  in pristine areas where the drainage is less efficient (Tessier *et al.*, 2003). In French Guiana, the gold rushes occurring since the middle of the 19th century affected mostly flat areas along the river network. Reducing conditions often occur in this environment, accentuated by disturbance of the prospected area's geomorphology.

## 9.6 Methylation of Mercury in Former Gold-mined Sites

In former gold mine flats, soil disturbance from ASGM activities has impeded soil drainage, which favours methylation of Hg. Guédron *et al.* (2011a) observed an increase in the concentration of various Hg species in a stream, between the entry and outlet of a former mined site, especially for both dissolved and particulate monomethyl-Hg (Fig. 9.4a). Total Hg concentration of suspended sediments increased along with increasing Hg concentrations of ASGM contaminated riparian soils. Although monomethyl-Hg represented less than 1% of the total Hg dissolved



**Fig. 9.4.** (a) Mean and standard deviation of dissolved (D) and particulate (P) total mercury (THg) and monomethylmercury (MMHg) concentrations in throughfalls, the stream source and the stream outlet of the former goldmine flat of the Combat Creek catchment (French Guiana) sampled between and during 14 storm events at the beginning and in the middle of the 2005 and 2006 rainy seasons. (Modified from Guédron *et al.*, 2011a.) (b) Dissolved (D) and particulate (P) total mercury (THg), monomethylmercury (MMHg) and total suspended solid (TSS) concentrations monitored at the outlet of Combat Creek (French Guiana) during construction and operation of an experimental gold mine in the former goldmine flat of the Combat Creek catchment in December 2006. (Unpublished data.)

in rainwater, throughfall and water draining the pristine Oxisols, it reached 2–3% in water draining the exploited soils. A comparable trend was observed for particulate monomethyl-Hg. Unlike Oxisols, which tend to retain or transform the monomethyl-Hg originating from the canopy and litter, soils contaminated by former eluvial gold mining are sources of both dissolved and particulate monomethyl-Hg (Fig. 9.4a). Between the entry and outlet of the former mined site, the specific flux in the stream (flux per unit area of the catchment) of dissolved and particulate monomethyl-Hg increased six-fold and four-fold, respectively, while total Hg specific flux remained stable for the dissolved fraction and doubled for the particulate fraction (Guédron *et al.*, 2011a).

Former gold mining activities dramatically disturb the geomorphology of prospected areas.

Many zones of stagnant water remain even several decades after the mining activity, leading to the accumulation of organic matter under anoxic conditions. These stagnant waters and, to a lesser extent, the pore waters of water-logged soils, are highly enriched in monomethyl-Hg (up to 0.8 ng l<sup>-1</sup>), containing 10–100 times the concentrations in waters draining the Oxisols (Guédron *et al.*, 2011b). Because of the abundance of sulfide and reduced Fe in these waters, methylation, favoured by the high Hg and organic C, can be attributed to sulfate and Fe-reducing bacteria (Ullrich *et al.*, 2001; Benoit *et al.*, 2003). Dissolved and particulate monomethyl-Hg is mobilized when production zones are connected to the drainage network during intense rainfall events. This mobilization is expressed by sudden peaks of monomethyl-Hg concentration in the stream, the strongest ones being observed

at the beginning of the rainy season, before the areas of stagnant water are replenished or diluted (Guédron *et al.*, 2011a).

In many Amazonian regions, eluvial gold mining is currently practised on formerly mined sites. Far more than deforestation and the removal of superficial soil layers, the highest particulate emissions are caused by excavation of diversion canals, which are subsequently used to supply water to a site's installations and to wash auriferous gravels, before digging a settling pond. A full-scale simulation of a gold mining operation at a site at Combat Creek (French Guiana, unpublished data), without use of Hg, pointed to large increases in Hg fluxes at the start of the operation: approximately 10 times more total Hg and 50 times more particulate monomethyl-Hg were released downstream of the mining site (Fig. 9.4b). Dissolved Hg fluxes increased less markedly, and dissolved monomethyl-Hg fluxes even decreased temporarily (Fig. 9.4b). Particulate Hg emissions remained high during rain events, because of erosion of deforested areas on the mining site. In the long term, these cumulative Hg emissions to the drainage network can be higher than inputs due to the opening of the sites. In particular, it is advisable to avoid overflowing of settling basins into rivers, because these basins act as zones of water stagnation. The highest concentrations of dissolved monomethyl-Hg observed in two basins studied (1.4 and 2.5 ng l<sup>-1</sup>) (Guédron *et al.*, 2011b) are similar to those recorded in storage dams (Boudou *et al.*, 2005; Muresan *et al.*, 2008), at the sediment–water interface. In the settling basins, high concentrations of dissolved organic matter, sulfates and Fe-oxides indeed favour the activity of Fe- and sulfate-reducing bacteria.

## 9.7 Recent Legislative Attempts to Reduce Mercury Emissions and Methylation

Since 2006, legislation in French Guiana has improved semi-industrial gold mining practices by prohibiting the use of Hg and replacing it with techniques that combine concentration by gravity and centrifugation. This legislation also requires construction of closed water circuits to strip off the gold-bearing layers of soil or sediment, thus decreasing emissions of fine Hg-rich

particles to rivers during mining operations. Besides improving mining practices, the most critical points for miners are to reforest sites to avoid Hg methylation after mining activities. Rapid drainage of the settling basins, followed by rapid revegetation, appears to be the best method to decrease post-mining Hg and monomethyl-Hg emissions (Guédron *et al.*, 2011b). The success of rehabilitation depends on human intervention to restore soil fertility, which includes reconstituting physico-chemical characteristics and recovering biological functions (Loubry, 2002; Schimann *et al.*, 2007). These interventions have to be prepared before mining operations by sampling local representative plant species and building a nursery. Next, revegetation requires covering the worked materials with an organic matter layer (stored during excavation of the organic horizon, the first step after deforestation), in which pioneer species and then the local species grown in the nursery are planted.

Since such promising practices are recent, not enough time has elapsed to evaluate their short- and medium-term impacts on Hg emissions and methylation. In particular, the fate of Hg methylation in deep and sub-surface groundwater of rehabilitated soils must be studied further. Although little to no information about the drainage capacity of these soils is available, it is probable that before they recover an aggregated structure that allows drainage, they will become saturated during rainfall events. Therefore, this disturbed material, consisting of an Fe-rich soil horizon and fine Hg-rich particles from settling ponds, might become a sub-surface source of monomethyl-Hg in groundwater under anoxic conditions.

## 9.8 Conclusions

Artisanal small-scale gold mining, both at present and in the past, has had a major impact on soils and ecosystems. The most crucial risk identified is the use of Hg to amalgamate gold. The impacts are not only local, as in areas directly affected by the working of auriferous deposits, or downstream from mining sites due to increased release of fine Hg-rich particles into the drainage network and food-chain contamination, but also global, via atmospheric emissions.

The Hg used in eluvial gold mining is added to the already important geochemical background of tropical soils. Indeed, soils of humid tropical regions are naturally rich in Hg, because of their high contents of carrier phases, in particular Al- and Fe-oxyhydroxides. Over long periods of time, these soils have accumulated Hg resulting from (i) the intense weathering of rocks, which nevertheless have low concentrations of Hg, and, more particularly, (ii) the input of atmospheric Hg derived from degassing of the Earth's crust and oceans, or from long-term anthropogenic emissions. This accumulation took place simultaneously with pedogenic processes that have shaped soil development, thus leading to great variability in Hg content linked to the diversity of tropical soils. The Hg used in ASGM activities can be stored in soils under its divalent form, as natural Hg, because tropical soils have high Hg-storage capacities. On gold mining sites, large quantities of anthropogenic Hg can be found in the form of droplets of elemental Hg or gold-Hg amalgams.

Although soils generally behave as a sink for Hg, from natural or anthropogenic origins, they can also become a source. By destroying the vegetation and soil cover, gold mining increases the erosion and transfer of soil particles enriched in Hg towards rivers. Contamination of the aquatic food chain by Hg results, above all,

from erosive practices that export both natural and anthropogenic Hg.

Artisanal small-scale gold mining affects most flat areas along river networks, where reducing conditions in hydromorphic soils favour atmospheric Hg emission. Above all, by reworking the soil, gold mining disturbs local hydrological and geochemical conditions, which then become favourable for Hg methylation. In this way, settling basins of present-day sites, but also flat riparian areas affected by former gold mining, act as biochemical reactors producing monomethyl-Hg, the most toxic bio-accumulative form of Hg.

Although the use of Hg has been officially prohibited in French Guiana since 2006, being replaced by techniques combining concentration by gravity and centrifugation, its use is common in other parts of the developing world. However, even when Hg amalgamation is not used, gold mining without any precautions creates conditions that favour the transport of Hg already present in the soils to river systems and its transformation into monomethyl-Hg. The risk of Hg contamination for humans thus tends to eclipse the other problems arising from ASGM operations. In fact, ASGM also causes complete deforestation of the areas exploited and consequently a loss of biodiversity and ecosystem functions, landscape modifications and soil degradation.

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# **Land-use Change Impacts on Soil Processes**

**Tropical and Savannah Ecosystems**

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*Edited by*

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