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Confidential document

Removal of barriers to the introduction of cleaner artisanal gold mining and extraction technologies in the Ingessana Hills, Blue Nile State, Sudan.

Part A : Environmental assessment

Final Report

BRGM/RC-53589-FR
March, 2005

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Study carried out as part of
UNIDO Contract No. 03/087. Project No. EG/GLO/01/G34.
Activity code: 420C51

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Executive summary

Introduction

This survey is part of a larger UNIDO programme (EG/GLO/01/G34) funded by the Global Environment Facility (GEF) and titled ”Removal of Barriers to the Introduction of Cleaner Artisanal Gold Mining and Extraction Technologies”. The long-term objective of the UNIDO/GEF program is to assist a pilot suite of developing countries, located in several key trans-boundary river/lake basins, in assessing the extent of pollution from current artisanal mining activities. Further objectives are to introduce cleaner gold mining and extraction technology that minimises or eliminates mercury releases, and to develop capacity and regulatory mechanisms that will enable the sector to minimise negative environmental impacts.

In response to a request from the Government of Sudan and as part of the overall UNIDO project, a contract was signed in July 2003 between the United Nations Industrial Development Organization (UNIDO) and BRGM for carrying out environmental and health surveys and assessments in selected gold-mining areas in Sudan. The operation was implemented by French teams (BRGM, University of Montpellier and University of Bordeaux) and Sudanese teams from the Geological Research Authority of Sudan (GRAS) and the University of Nileen. BRGM, in cooperation with GRAS, was in charge of the coordination of the environmental assessment and the University of Montpellier headed the health assessment survey. The sampling campaign and health survey took place from March 29th to April 18th, 2004 during the hot dry summer weather before the rainy season and the main mining season.

The aim of this study was to collect environmental and health data in the Gugub and Khor Gidad villages of the Bau district in the Ingessana Hills (Blue Nile State of Sudan). This area was previously selected by UNIDO (EG/GLO/1/G34 – BTOMR *of C. Beinhoff and L. Bernaudat, UNIDO)* for an environmental and health survey of the communities living in the surroundings. The ultimate goal of this project is to formulate recommendations on the gold mining practice in order to avoid significant local and regional pollution. A previous report (Récoché *et al*., 2004) details the information collected in the field and the sampling methodology.

Mining practice and use of mercury

Use of mercury in the area is quite recent and depends on the type of mining activity. Artisanal Small Scale Mining (ASM) in the Ingessana Hills varies somewhat between villages, with some identifying an active participation in the activity and others a decline depending on season and gold-bearing quartz vein discoveries.

Artisanal gold mining in the Ingessana Hills started in 1996. Intensive use of mercury in the area is quite recent (about 3 years or less) and was mainly developed in the Gugub area where gold was first discovered, and in Khor Gidad after a gold rush in September 2003. During our mission, these two sites were the only ones in activity; the village of Khor Gidad was the site of gold-bearing quartz-vein extraction and ore processing, whereas the village of Gugub had processing sites only. The other sites mentioned in the sociological reports carried out in the district by Prof. Khalil A. Al Medani (2003) (i.e. Turda, Khor Neiwi) are alluvial gold-mining sites where no mercury was used and that are presently abandoned.

Miners pan alluvial and eluvial gold when local streams are flowing during the rainy season between July and December. They do not use mercury and recover only visible gold. Results of Hg analyses carried out for this study confirm this point: soils, tailings and sediments sampled around alluvial panning sites are not contaminated by Hg.

During the dry season, due to a lack of water in pit sites, only primary gold associated with quartz veins is mined. The procedures used are typical of very poor people using simple and traditional practices. Mercury is used only to recover gold from this primary ore.

Artisanal gold mining in Gugub is practised by both Dawala and Ingessana tribesmen without legal titles. Most of them mine and process the ore in small groups that are basically a family affair. Many of these activities were performed by women (13-35 years old), including the hard tasks of digging and excavation. Men are only involved in mining at depth and in the roasting phases. There is no major flowing river close to the mining and processing areas, only seasonal drainage and in summer small pools along the main wadis. Mercury is not used on the mining site, but the selected ore is transported to the village for manual crushing and milling, and panning.

Mining of gold-bearing quartz veins was the only type observed during the field mission. The extraction of shallow ore is mostly done by women in a rather muddled way without mechanical tools. Men are only involved in mining at deeper levels. No explosives are used. The material is manually hoisted and then sorted visually in an empirical way, in order to try and concentrate the most probable gold-bearing material. Artisanal primary gold mining usually entails visual selection of mineralised rock pieces. At this stage, the selected ore is transported to the village. Crushing, milling and panning are done manually by women in the yard of “family units” combining several huts of the same family. Panning is done in excavated pools using traditional wooden pans. The tailings are dumped around the huts outside the “family units”. Panning efficiency using the traditional wooden pan is ~50%. Apparently, all fine gold grains remain in the fine fraction of the tailings. Panning tests on waste heaps during the mission indicated common gold specks. After crushing and/or milling, the pan concentrate is sent home or to the gold-merchant shops for amalgamation and roasting. Mercury is used to extract the fine gold particles from the last panned concentrate. The way of handling mercury in gold amalgamation is unsophisticated. After a last panning in the yard, Hg is poured onto the concentrate with water and is mixed with bare fingers to make the amalgam. After thorough mixing, the amalgam is squeezed through a piece of cloth and the excess Hg is recovered for reuse. The miners collect the amalgam by hand, without any precautions. After that, the remaining amalgam is transferred to an open plate or frying pan for roasting. In the private yard there is no specific place for amalgamation and roasting. The gold amalgam is roasted in bonfires outside or inside the huts, a task done especially by the men. Daily, they roast the amalgam without taking any precautions. The roasting operation can occur in the village close to the dealer's shop where they buy mercury; in the yard of the "family unit", or in the huts (usually the ones used for cooking). The diameter of amalgam burned during the demonstrations carried out during our visit ranged from 3 to 8 mm. We expect that the duration of the burns (~10 minutes) is too short and the temperature produced by the bonfire is too low to burn all the mercury. Roasting tends to be incomplete and at least 15-25% of the *"doré"* sold to dealers contains residual mercury.

Gold production estimates based on two independent sources (worker's production and dealers) gave similar results: the quantity of gold produced from quartz veins in the two villages is 75-300g Au/day or 22.5-90kg Au/annum. Workers and dealers probably underestimated their own production and actual values may be higher.

We calculated that to produce such quantities (100-300 g Au/day) from the Gugub sites, 800 to 1000 workers must be involved and gold grades should be 30 to 72 g/t respectively. According to the available data and our observations (average gold grades measured by GRAS is <5 g/t and 300 families living on the sites), the works in Gugub cannot produce the quantity of gold mentioned before from quartz-vein mining alone. A large part of the gold sold during the dry season (probably 50%) likely comes from alluvial production and also from gold reserves made by workers during the rainy season. According to our field observations and estimations, the use of mercury in Gugub district is between 250 and 500 g Hg per household of artisanal miners. Taking into account these data, the ratio of Hg lost over Au produced is probably over 3 in the Gugub area.

System analysis and sampling strategy

The sampling strategy followed a risk-assessment approach, considering the various sources of mercury, its transfer and pathways, and the potential targets.

The ~300 artisanal gold-miner families and the 10 to 15 local gold-merchant shops in Gugub and Khor Gidad constitute the same broad mercury hotspots. Potential risks to the ecosystem were considered to be minor. The main targets identified are local people practising gold concentration at home. The shops and surroundings represent further specific hotspots. We identified four sources of mercury loss in the environment:

- Wrong manipulation of mercury in the shop or at home;
- Loss of Hg on the ground or in the tailings during amalgamation;
- Evaporation during roasting;
- Occasional panning of tailings in the pools.

	Items Considered	Level of occurrence
SOURCES	• Shops where Hg is stored	✱✱
	• Accidental Hg spills during amalgamation (huts & shops)	✱✱✱
	• Amalgam roasting in the hut	✱✱✱
	• Waste dispersal	✱✱
	• Contamination of sediments during panning on residues in Gugub	✱
TRANSFER & PATHWAYS	• Household dust contamination	✱✱
	• Hg vapour dissemination contaminating the house and its environment	✱✱✱
	• Soil contamination in the vicinity of contaminated huts	✱✱✱
	• Sediment transportation	✱
	• Transfer to the biological chain (fish)	✱
HUMANS TARGETS	• Hg inhalation during roasting	✱✱✱
	• Household dust and soil ingestion (mostly children in huts or yards)	✱✱✱
	• Contaminated maize and sorghum consumption	✱✱
	• Fish consumption (rare)	✱
	• *Contaminated poultry consumption*	not considered in this study

In Gugub and Khor Gidad, sampling focused on media potentially submitted to ingestion by local people (mostly children) and poultry. These include: household dust as amalgam roasting sometimes is done in huts; soil around the huts of artisanal gold miners, in the yard of a "family unit" that combines several huts and in the main village square; and tailings and processing residues around huts and in gardens where vegetables are grown. Hg contents in air were also measured outdoors and in the huts under different conditions.

Based on information from the sociological survey, reference houses were identified in each village: the school and mosque yard in Gugub and recent "enclosure dwellings" outside the mining area of Khor Gidad. The selection criteria were based on a lack of artisanal mining activity for the concerned household.

The objective of sediment sampling was to check Hg mobility in the drainage around the two villages of Gugub and Khor Gidad, and in the main collector Wadi Maganza. The strategy was adapted to field conditions; sediments were taken along narrow stream beds where possible; we collected both sand (stream beds) and silty black sediment (stream banks).

Sampling conditions for fish in the Gugub and Khor Gidad sites were particularly unfavourable; Wadi Maganza and its tributaries had dried up completely, making it impossible to catch any fish in this area. The sociological study also indicated that fish is consumed only occasionally and then mainly dried. Fishing is an occasional occupation, mainly practised by the younger generation. According to local people and the Sudanese participants, the Roseires reservoir was the only site where we could find fish of different species and size, as requested by the protocol.

Due to the lack of fish elsewhere in the selected area, fish sampling was thus mainly carried out in the Roseires reservoir about 50 km to the east of Gugub (to test contamination of the Nile at this location, but not to interpret Hg mobilisation from the Gugub area) and in a wadi between Gugub and Khor Gidad, which contained a small water hole that was not directly connected with the gold-washing zone and the village of Gugub.

Solid samples were analysed by Lumex RA915 at BRGM in France. Air-quality monitoring was done on site using the Lumex. Fish samples were analysed by CV-AAS at the University of Bordeaux (LEESA) and vegetables by atomic fluorescence in the BRGM laboratory.

Contamination due to amalgamation practices

According to analysis of the process, the most probable contamination of soil is related to solid deposition of mercury during the amalgamation process, or to atmospheric deposition of mercury during roasting, and to the dissemination of household dust near artisanal miner huts.

Soil in the yards is contaminated by Hg. The average geochemical Hg content in Gugub and Khor Gidad is around ten times (medians ranging from 640 to 1,213 ng g^{-1}) the local background (100 to 150 ng g^{-1}). Contamination is point sized with probable nugget effects. Higher values in the villages (up to 10^6 ng g^{-1} in Khor Gidad and up to 27,626 ng g^{-1} in Gugub) are related to amalgamation zones where Hg droplets were visible after panning. The panning and amalgamation zones, with values several times higher than places with values close to local background, are the main hotspots. A school yard in Gugub shows background Hg contents of 106 ng g^{-1}.

Contamination due to amalgam roasting

The location of the main roasting site was rather difficult to identify. In Khor Gidad, outdoor roasting seems to be the norm. In Gugub, the proportion apparently is about 50% outdoors and 50% indoors. Roasting is mainly done by men.

Significant contamination of domestic dust was also found in some huts and yards of artisanal miners (500-2,760 ng g^{-1} in Gugub and 123-840,000 ng g^{-1} in Khor Gidad). It is clear that indoor amalgam roasting can significantly contaminate the dust in the huts, but there are no big differences between the Hg contents in soils and in domestic dust throughout the village, and no significant difference according to dust location (hut with or without roasting). It was impossible, at this stage of the investigation to identify the ratio between contamination of soil through amalgamation or through roasting. The information supplied by inhabitants commonly is imprecise, but these results show at least that the contamination is rather general and homogeneous at the scale of both households and the village.

Monitoring of air quality inside and outside huts showed that Hg concentrations may reach relatively high concentrations during the roasting phase (≥50,000 ng m^{-3}). However, in the worst case, the exposure of artisanal miners during roasting (around 10-15 mn per day) was relatively short compared to the exposure limits for professional workers (25,000 or 50,000 ng.m^{-3} for an 8-h exposure according European and North American standards). However, as some roasting is done in huts, we should also consider the possible exposure of children.

The roasting of amalgam usually generates two Hg peaks above 24,000 ng m^{-3}. The first peak appears when Hg evaporates from the amalgam; the second one, a few minutes later, is probably due to a late recondensation of mercury aerosols emitted during roasting. This condensation phase indicates that a large part of mercury emitted in the hut remains inside and therefore could accumulate in dust on the floor, on walls, or on foodstuff hanging in the hut. The second point is that this condensation phase could concern the entire hut, unlike the roasting period (local evaporation near the fire). All people present in the hut at this time could thus inhale this mercury vapour. The condensation effect is low in huts that allow evacuation of smoke through openings at the junction of walls and roof. During outdoor roasting, the duration of the period of high mercury concentrations is shorter than in a hut (around 100 s compared to 500 s in a hut) and the second peak of probable condensation of mercury vapour is absent.

Remobilisation of Hg in stream sediment

The remobilisation of Hg from processing zones to local streams seems very low. The Hg contents of wadis and khor flowing from the villages of Gugub and Khor Gidad are similar (median <200 ng g^{-1}) with higher contents near amalgamation zones (villages) and a rapid decrease of Hg contents some hundreds of metres downstream from the mining villages. Hg concentrations in sediments of the main collector Wadi Maganza are also relatively low (42-148 ng g^{-1} on a dry weight basis) and do not show important levels of contamination with regard to the usual guideline values for sediment management in Europe or North America. It is not possible to compare the results obtained on dry samples from the villages of Gugub and Khor Gidad with samples taken somewhere else in flowing rivers. The sampling conditions (focused on dry samples with organic matter) partially explain the high values encountered. Hg contamination of sediments exists in the villages where amalgamation and roasting take place, but seems restricted to a narrow zone a few hundred metres wide, and, at the present time, without apparent contamination downstream through Wadi Maganza.

Contamination from tailings and impact on stream

The phases of grinding, amalgamation and roasting generate heaps of mixed tailings, residues, ash or waste, that can be several cubic metres in size, commonly dumped near the zones of operation, in or around dwelling enclosures, or even in gardens. Hg analyses of such tailings show a heterogeneous contamination depending on their composition, which locally can be important (62,300 and 72,500 ng g^{-1} in Khor Gidad). Their number and location in gardens or dwellings is a problem to be taken into account for future environmental management operations in the area.

Workers indicated that during the rainy season some of the tailings and residues are panned in pools in the Khor Alyas*,* south of Gugub. The highest Hg contents in sediment (1,066 to 1,649 ng g^{-1}) are located along this stream bed, where aquatic life is unknown, but where a water well supplying Gugub with drinking water is located downstream. Control analyses of the water well should be carried out in priority.

Consumption of fish and vegetables

Another, minor, risk of exposure is related to the consumption of fish and vegetables (sorghum and maize).

There is a poor correlation of mercury-contamination levels in fish species and artisanal gold mining, because of the difficult sampling conditions. The level of contamination in fish-muscle samples (15 species - 108 individuals) is very low and none exceeded the WHO safety limit of 2.5 µgHg/g on a dry-weight basis; mean Hg concentration was 0.246±0.048 µg/g and 0.49±0.10 µg/g for the carnivorous species. Compared with Zimbabwe for fish of a similar size, the mean Hg concentrations were about ten times lower. Analysis of the results relating to the level of mercury contamination in the fish must necessarily bear in mind the constraints imposed by sampling conditions and the lack of any direct relationship with the gold mining site and the village of Gugub. The minor consumption of fish in the area (only 2% of the people eat fish occasionally) does not seem to constitute a major risk of Hg exposure. The data from wadis directly affected by gold-mining sites using amalgamation procedures must be considered insufficient to draw conclusions concerning either the consumption or not of fish, or health-related matters for this area of Sudan.

Sorghum and maize are the main vegetables consumed, at least during the dry season. The average Hg contents in garden soil around the “family units”, 130 and 280 ng g^{-1} in Khor Gidad and Gugub respectively, are close to background levels, and below the UK and Canadian standards of permissible Hg concentration in agricultural soil that range from 1,000 to 8,000 ng g^{-1}. This indicates low mercury remobilisation, probably due to Fe-rich laterite acting as a natural barrier that attenuates the dispersal of Hg. The Hg content of analysed sorghum and maize is very low and does not present any specific risk, but significant quantities of mercury are present in the dust deposited on vegetables hanging from the roofs of huts were roasting takes place. This mercury is eliminated by simply washing with water. However, these results on sorghum and maize should be controlled at a later stage, as apparently they may contribute to a more precise evaluation of the daily mercury intake for the local population.

Recommendations

This study was conducted during a short period, which does not allow precise conclusions in terms of impact assessment. Some aspects would require further specific controls, such as:

- In the wadis and khor, especially in Wadi Maganza, the sampling of fish and sediments should be extended during the rainy season to evaluate the real level of contamination in the river system. The first results indicate that the risk of high contamination in fish is low.
- Environmental assessment concerned only the environment of artisanal miners. Contamination of gold shops and surroundings was shown to exist in both villages. We suspect that roasting is incomplete and at least 15-25% of the “doré” contains residual mercury. To complete this assessment, particular attention should be paid to the more exposed population of dealers, merchants and their families.
- Results on sorghum and maize should be controlled during a further stage, as they may contribute to the evaluation of daily mercury intake by the local population. The washing of hands and vegetables should be a priority, even if sometimes water may be scarce.

As the gold-mining practice of local artisanal miners is quite recent, very traditional and with a limited use of mercury, there is no pressing need to propose a major programme for developing alternative technologies on a short-term basis. However, we strongly recommend changing some habits in the artisanal mining and processing practices. Change in local mining practices would require a raised awareness campaign with education of the population and especially women as they are mainly involved, concerning the risks they and their children face. Action should focus on amalgamation and roasting procedures in order to promote a safer working environment.

- The main objective is a change of the location where amalgam is roasted. Outdoors roasting is strongly recommended and exposure to mercury vapours can be avoided through simple technological improvements such as retorts. Roasting the amalgam does not seem to be a private and confidential activity, as it is commonly carried out in the street or in shops. This fact may help to persuade the local artisanal miners to find appropriate spots dedicated to roasting and sufficiently distant from the village. Such places should be designed to avoid dispersion of Hg in the environment. The presence of children and pregnant women should be avoided during roasting.
- Authorities need to ensure that all amalgamation is carried out in cemented places and that all amalgamation tailings are stored in appropriate cemented storage areas that prevent dispersal of Hg contamination onto adjacent land and into drainage.
- Careful clean-up of contaminated huts is recommended in order to decrease the Hg content of domestic dust.
- Amalgamation zones located in “enclosed family units” must be marked and fenced in order to prevent Hg ingestion by children or animals.

As use of mercury is recent, the most urgent requirement is to prevent any new Hg input into river sediments by stopping, or at least strictly controlling, the panning of contaminated tailings in pools during the rainy season.

Acknowledgements

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In Khartoum, Mr. Jebamalai Vinanchiarachi, the UNIDO Representative for Sudan, and Dr Abdelrazig Obeid Mohamed Ahmed, General Director of the Geological Research Authority of the Sudan (GRAS) and Country Focal Point (CFP) secured technical and administrative support. Their assistance and that of the UNIDO Coordinating Unit Staff in Vienna, Dr. Christian Beinhoff and Dr. Marcello Veiga, are gratefully acknowledged.

The authors are indebted to the assistance of Ariab Mining Company management, who helped us during preparation of the field camp in Khartoum.

The GRAS delegated Mohamed Ibrahim Suleiman (Head of the Chemistry laboratory, ACFP), Adel Osman El Rashid and Said Abdallah Salih (Geologists), Shams El Din El Dao and Mohamed El Hassan (Drivers) to participate in all field work. The authors are grateful for their efficient support to collect data, their local knowledge and their advice concerning local practices.

Dr. Khalil A. El Medani, Head of the Department of Sociology at El-Nileen University (Khartoum) joined the team halfway through the field work. The authors are very grateful for his support on knowledge on local communities, notably acquired during his sociological study in the area.

Special thanks go to Ibrahim Mohamed Toum, GRAS representative in Ad Damazin, who greatly facilitated the contact with local authorities and who assisted us during preparation of the field mission.

BRGM is grateful to the Commissioner of Bau district and the Ingessana Tribal chief (Omda) for their respective consents before approaching the artisanal mining community in and around Gugub.

In Gugub, the People Committee representative and Prof. Zu Lkifle Yahia, school teacher, were the key persons of the community. Environmental and Health Assessment Survey efforts would not have been possible without their consent and daily assistance.

Special thanks go to Suleiman Yaya Mohamed and Mohamed Djakalo, the two local workers from Gugub, hired on site to help in the sediment and soil sampling.

Finally, the authors are grateful to Dr Christian Leveque (CNRS, Meudon, France) who determined the species names and food regimes of the fish collected during the mission to Sudan, and to Ph. Freyssinet and V. Laperche (BRGM) who agreed to review and comment this draft report.

Contents

List of illustrations

List of appendices

1. Introduction

This survey is part of a larger UNIDO program (EG/GLO/01/G34) funded by the Global Environment Facility (GEF) and entitled **Removal of Barriers to the Introduction of Cleaner Artisanal Gold Mining and Extraction Technologies**. The long-term objective of the UNIDO / GEF program is to assist a pilot suite of developing countries, located in several key trans-boundary river and lake basins, in assessing the extent of pollution from current artisanal-mining activities. Another objective is to introduce cleaner gold-mining and -extraction technology that minimises or eliminates mercury releases, and to develop capacity and regulatory mechanisms that will enable the sector to minimise negative environmental impacts.

In response to a request from the Government of Sudan and as part of the overall UNIDO project, a contract was signed in July 2003 between the United Nations Industrial Development Organization (UNIDO) and BRGM, in order to carry out environmental and health surveys and assessments in selected gold-mining areas in Sudan.

The village of Gugub in the Ingessana Hills (Blue Nile State) was selected by UNIDO (EG/GLO/1/G34 – BTOMR *of C. Beinhoff and L. Bernaudat, UNIDO)* for implementing the environmental and health survey of the communities living in the surroundings. In 1997 gold was discovered in the central part of Ingessana Hills and the recent discovery of gold around Gugub village has attracted many people, especially those displaced by civil war in the southern parts of the region. Today, the Ingessana district is characterised by the presence of about 800 multi-ethnic individuals practising alluvial and primary artisanal gold mining and working with mercury to recover gold under very poor conditions. At the moment, the area is characterised by the presence of two main villages, Gugub and Khor Gidad, where artisanal gold miners process alluvial and primary quartz-vein ores. The ultimate goal of this project was to formulate recommendations on gold-mining practice in order to avoid significant local and regional pollution.

In accordance with UNIDO and GRAS representatives, BRGM planned to do the field survey in March, 2004 before the rainy season. Sampling and the health survey took place from March 29th to April 18th, 2004.

A previous report (Récoché *et al*., 2004) details the information collected in the field and the sampling methodology.

This final report summarises the methodological aspects as a well as the field information and presents the analytical results of the environmental survey. The report concludes with an evaluation of Hg contamination in various media.

2. Aims and objectives

The aim of this study was to collect environmental and health data in the Gugub and Khor Gidad villages of the Bau district, to assess the level of mercury exposure in the local communities and its potential impact on the environment. The district is located in the Ingessana Hills, Blue Nile State of Sudan, where the practice of artisanal gold mining has been identified. Another small village, Taga was added as a reference village (i.e. a village without a mining history).

The data will also be used to identify appropriate technologies or good practices for reducing the risk of mercury exposure to humans and of mercury contamination in the environment.

Specific study objectives of the environmental assessment are outlined below:

- To identify and evaluate the possible means of exposure of villagers to mercury released by small-scale artisanal gold mining following a risk-assessment methodology.
- To sample various environmental media. Different media were sampled according to the protocols recommended by UNIDO (Veiga and Baker, 2003).
- To characterise the source of the pollution and its potential dissemination in the environment.

The environmental assessment was closely coordinated with the health survey in order to support the interpretation of the health data and to evaluate the level of exposure of local population to mercury.

3. Organisation and planning

Most of the technical details and planning are described in the field report (Récoché *et al.*, 2004). The following section summarises some key steps of the project.

3.1. PROJECT TEAM OF THE ENVIRONMENTAL SURVEY

3.1.1. Members of the project team

The members of the project team for the duration of this field mission were as resumed in Illustration 1.

Names	Occupation	Country	Organisation	E-mail
Environmental Team				
RECOCHE Gilles	Geologist Team Leader and Head of Environmental Team	France	BRGM	g.recoche@brgm.fr
IBRAHIM Mohamed Suleiman	Geologist Assistant CFP	Sudan	GRAS	Gras@sudanmail.net
GHESTEM Jean-Philippe	Geochemist	France	BRGM	jp.ghestem@brgm.fr
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Health Team				
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EL BASHIER Abdul Hadi Mohamed	Surgeon	Sudan	Singer Hospital Sinnar State	
LALOT Marie-Odile	Medicine Doctor	France		mo.lalot@brgm.fr
EL MEDANI Khalil Abdalla	Sociologist	Sudan	University. of Nileen	Khalidabdalla@hotmail.com
FENET Hélène	Epidemiologist	France	University of Montpellier 1	hfenet@iup.pharma.univ-montp1.fr

Illustration 1 - Members of the project team involved in the field mission

3.1.2. Local assistance

The GRAS delegated Mohamed Ibrahim Suleiman (Head of the Chemistry laboratory, ACFP), Adel Osman El Rashid and Said Abdallah Salih (Geologists), and Shams El Din El Dao and Mohamed El Hassan (Drivers) to participate in all field work.

Two local workers from Gugub were hired on site to help in the sediment and soil sampling and in the panning operations.

Dr. Khalil A. El Medani, Head of the Department of Sociology at El-Nileen University (Khartoum), hired by UNIDO, joined the team when field work was ongoing to support the Health assessment work.

The Commissioner of Bau village arranged the participation of two nurses of the Bau hospital in the Health assessment field work.

The employment of a cook and an electrician was also necessary at the base camp located at Bau.

3.2. PLANNING

The main steps of the projects are summarised as follows:

- Signature of the contract: July 7^{th}, 2004.
- Field campaign in Sudan: March 29^{th} to April 18^{th}, 2004. The details of the tasks performed in the field are described in the Field Report (Récoché *et al*., 2004).
- Analysis and data processing: from June to September, 2004.
- Final Report: March, 2005.

4. Description of field conditions

4.1. GENERAL CONTEXT

4.1.1. Location

The Gugub artisanal gold mining site selected by UNIDO lies in the middle of Ingessana Hills, some 80 km to the southwest of Ad Damazin town, capital of the Blue Nile State. The area bounded by latitudes 10°00'-12°00'N and longitude 33°45' eastwards to the Sudan-Ethiopia border is geographically referred to as the southern Blue Nile region (Illustration 2).

Blue Nile State is administratively divided into four districts: El Damazin, Roseires, Kurmuk, and Bau. Bau and Roseires districts are the main areas where artisanal gold mining occurs. The Ingessana Hills area comprises major artisanal gold-mining activity around Bau town. The artisanal sites are scattered around Gugub village, which lies ~10 km northwest of Bau town; the administrative center of the district.

During the latest national census of 1993, the total population of the region was 413,694. Bau locality, where the targeted artisanal gold mining occurs, has a population of ~100,000 (Khalil A. Al Medani, 2003).

The region is full of economic and natural resources. Rain-fed macro- and micro-scale farming, wood cutting, charcoal producing, artisanal gold mining, and commercial fishing are the major economic activities in the southern Blue Nile region. The region has more than one million Fedans of arable land and grazing area (1 Fedan = 4,200 m^2). Food crops grown include sorghum, maize, sesame, sunflower, vegetables, and fruits (Khalil A. Al Medani, 2003).

This area is not covered by topographic maps, except for one at scale 1:250,000 dated 1975 that was provided by GRAS. However, this map was too much out of date to be usable.

4.1.2. Topography and climate

The southern Blue Nile region is characterised by both flat clay plains and a hilly topography in the south and the southwest, with gentle slopes towards the north and southeast. Gently sloping pediments have drainage flow connected to the Blue Nile River system. Ingessana district is characterised by a range of hills rising from 800 to 1000 metres above sea level and expanding in a semi-circular form with a diameter of around 40 kilometres.

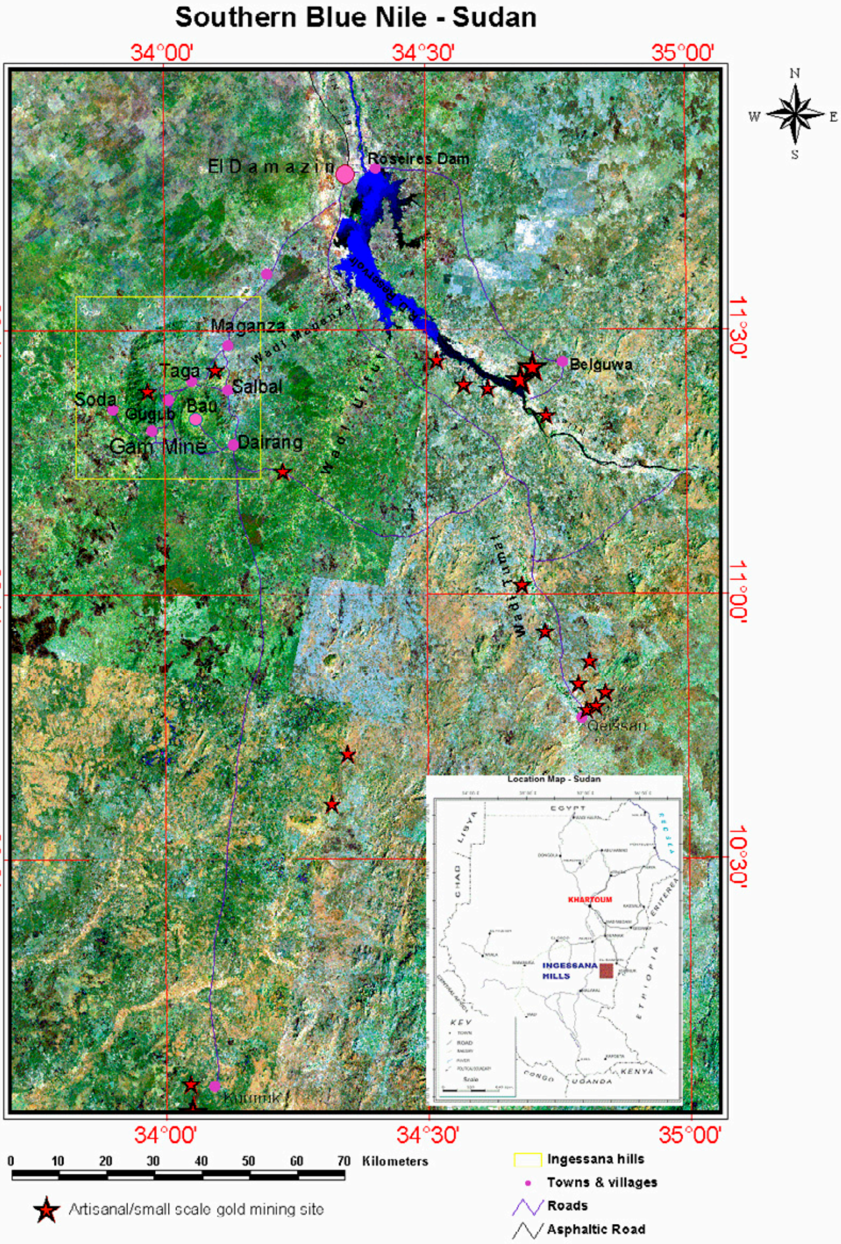

Illustration 2 - Location of the Ingessana Hills area.

The Blue Nile River is the major drainage landmark in southern Blue Nile region. The prominent seasonal tributaries (Wadi/ Khor) that emerge from the Ingessana massif in a radial pattern are wadis Timsah, Maganza, Ferri, and El Dom. Among these, Wadi Maganza virtually drains all northeastern parts of the Ingessana Hills where most artisanal gold-mining sites are located. Its seasonal waters end up in the Roseires Dam reservoir at a point some 20 km south of Ad Damazin town (Illustration 2). No flowing water was observed during this mission, although there were small pools along the main wadis (Illustration 21).

The region lies within the Savannah Zone with annual precipitation ranging between 600 and 800 mm. Dense bush and tall grass cover the hillsides and stream banks. Climatic seasons are defined by a hot dry summer (March-June), a hot wet autumn (July-October), a mild dry winter (November-February), and a very short spring (early March). Mean daily temperature ranges from 43 ºC in mid summer (April-May) to 20 ºC in mid winter (December-January).

The mission took place during the hot dry summer before the rainy season. From June to November, the area is very difficult to reach.

Gugub and Khor Gidad villages are located within a small valley and huts are built on slopes on both sides (Illustration 3 & 4). There is no major flowing river close to the mining and processing areas, only seasonal drainage. All the streams, khors and wadis were dry during our mission and there was no panning (Illustration 5).

In the dry season, the dominant wind direction is north-south; this reverses during the rainy season.

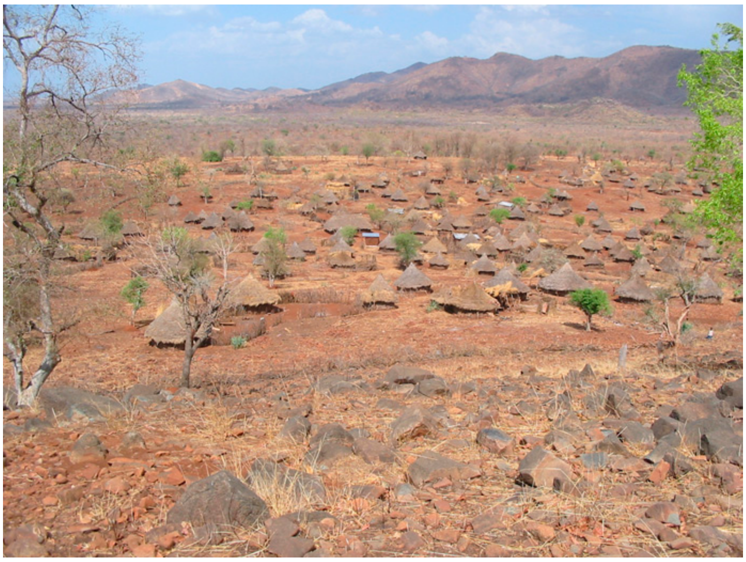

Illustration 3 - View from the NW of the central part of Gugub village

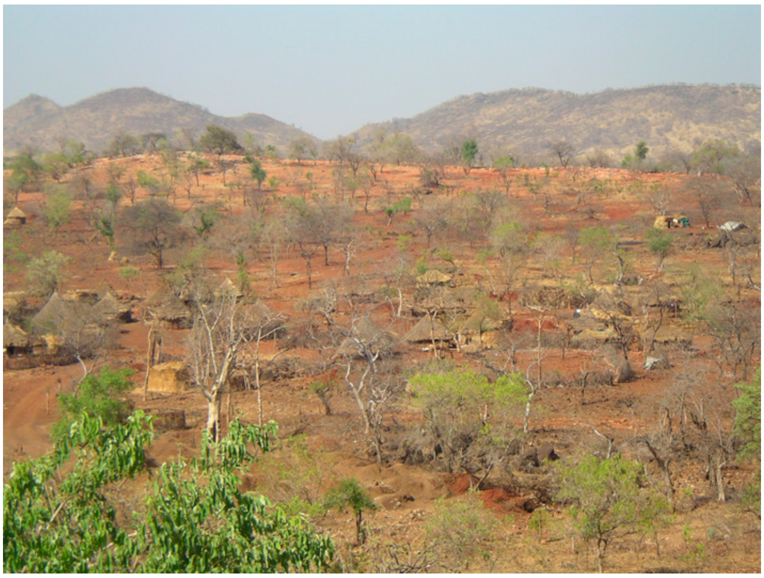

Illustration 4 - View from the SW of the central part of Khor Gidad mining area (gold-bearing quartz vein located on the top of the small hill behind)

4.1.3. Geological information

In Gugub and Khor Gidad, primary ore exploited by artisanal miners is vein-related gold mineralisation. The auriferous bodies are hosted by micro gabbro and associated altered rocks. Gold mineralisation is associated with NE-directed shear zones (e.g. Khor Feri shear zone) sub-parallel to the western contact between Bau granite and adjacent ophiolitic ultrabasic rocks (Elnour K. Mohamed *et al*., 2002). The quartz veins occurs as bodies of varying length (150-250 m) and width (a few centimetres to 2 m), dipping 30 to 45°NE, in en-echelon boudinage arrays and as lenticular pods. Fresh galena and arsenopyrite are the main mineralisation observed in quartz samples. Visible gold appears to be associated with iron oxide within sulphide boxworks.

Chip-sampling by GRAS in 2002 on eight auriferous quartz-vein sites of the Gugub area indicated low Au grades[1] at the surface (Elnour K. Mohamed *et al*., 2002).

During the rainy season, gold is panned from alluvial and colluvial deposits that form terraces along the main khors and wadis (Illustration 5).

[1] Values are given in chapter 4.2.3 (p.31)

Illustration 5 - (a) Alluvial panning area on Khor Shareban (Gugub);
(b) Area of colluvial workings (Gidad)

4.1.4. Sociological aspects

The information given in the following paragraph was mainly extracted from the sociological survey carried out in the district by Prof. Khalil A. Al Medani (2003) with complements collected during the field mission.

Ingessana are the indigenous Nilotic ethnic group that possibly has inhabited the Ingessana hills since the 16th Century. The second ethnic group is the Dawala, who have been displaced by war. Historically, Ingessana depended on livestock and on minor shifting cultivation in the lowlands beyond their mountains. Since 1997, the Ingessana district has attracted many people looking for gold. The first to come and live with the Ingessana were Dawala people from Kurmuk ~100 km to the south. About 185 families built their huts in Gugub village. Artisanal gold miners in the Ingessana Hills concentrate in Gugub, Taga, and Salbal villages. Gugub village of ~1,000 inhabitants is the major centre of activities. Artisanal gold miners are scattered in three sites at present. The biggest cluster of activities known as Khor Gidad is located ~7 km (driving distance) north of Gugub village. There are ~800 individuals who currently practise artisanal alluvial gold pitting, mainly along stream terraces. Within the Gugub artisanal gold mining community, Dawala account for ~80% of the ~185 households (~1,000 heads). The rest are Ingessana groups living at the fringes of the village or as isolated households on hill slopes. The bigger concentrations of sedentary Ingessana artisanal gold miners are found in Taga village ~5 km east of Gugub (~200) and Khor Gam–Rumailik ~7 km northwest of Gugub (~100).

The age of members of male Gugub artisanal gold miners ranges from 15 to 50 years, while most women miners and water providers at the Khor Gidad site are 15-35 years old. A few old men and women (>60 years) practise alluvial gold mining in shallow pits. Children are quite common at gold-pitting sites (10- 15%). Girls in the 10 to 13 age range constitute the majority of participating children.

Both Ingessana and Dawala families live in conical straw and thatch huts. Ingessana people build their huts either at the fringes of the villages or as isolated households on hillsides. Dawala families, however, live in groups. Excluding some of the shops, all dwellings, school class rooms, and the mosque in Gugub are built of straw and wood, even though some Dawala men are affluent enough to build stone or brick bungalows. In Gugub, there is no specific hut or place reserved for gold processing. The same hut is used for sleeping, cooking food, ore grinding, and amalgam burning. The huts of the same family are grouped together and surrounded by a wooden fence. This group of huts is called "family unit" or “enclosed family unit” in this report (Illustration 17). In August 2003, 53% of artisanal gold miners at Khor Gidad lived about half a kilometre from the mining pits, 10% lived three kilometres away, and 37% lived in Gugub ~4 km (walking distance) to the pits (Illustration 3, Illustration 4).

Being located ~50 km from the west bank of the Blue Nile, the community of Gugub and surroundings has no frequent access to fresh fish supplies. In the survey, only 2% of the people report eating fish occasionally. However, dry fish is available in the Gugub market.

4.1.5. Sites selected

Most of the data on artisanal gold mining and processing in the Ingessana Hills area may be found in the UNIDO reports entitled “Information about Ingessana Hills artisanal gold mining sites chosen for the Environmental & Health assessment” by Mohamed S. Ibrahim (November, 2003) and “Socio-economic sample study of the Ingessana Hills artisanal gold mining community, Blue Nile State,Sudan” by Prof. Khalil A. Al Medani, University of Nileen, Khartoum, (December, 2003).

During our short orientation survey, and according to the mission objectives, the visits focused primarily on the sites where mercury is used and on the area where the sociological study was made, in order to be able to subsequently correlate the environmental and health assessments.

Sociological reports, advise from their authors and a short orientation survey carried out during the first days of the field mission, allowed us to select three main targets to be studied[2]: the two main artisanal gold mining sites of Gugub and Khor Gidad, and Taga village as a control site (main activity of this Ingessana village was farming and mercury has never been used).

4.2. LOCAL MINING PRACTICES AND USE OF MERCURY

4.2.1. Types and location of mining activities

Artisanal gold-mining activities in the Ingessana Hills started in 1996 when a Dawala ethnic group displaced from Kurmuk district, including skilled artisanal gold miners,

[2] Details are given in the following chapter 4.2

discovered gold in quartz veins around Gugub village. They first started artisanal gold mining along the stream terraces and later on quartz-vein slopes.

In Gugub district, there are two seasonal types of mining activity:

- Miners pan alluvial and eluvial gold when local streams are flowing **during the rainy season** (July to December). Ancient or inactive panning sites are visible all around Gugub and Khor Gidad villages along one to several metres wide wadis and khor (Khor Alyas, Khor Abu Djal, Khor Shareban, Khor Gidad) (Illustration 5). In those sites, miners do not use mercury and recover only visible gold. No activity of this type was observed during our field work that took place during the dry season.

- **During the dry season**, due to a shortage of water in the pit sites, only primary gold associated with quartz veins and colluvium is mined. Miners indicated that mercury is used only to recover gold from primary ore and that primary ore exploitation is more recent than alluvial mining.

The sociological study mentioned that, today, a gram of gold produced from alluvium through panning has a higher price in the local market (US$ 9-9.5) than a gram of gold extracted from hard rocks through amalgamation (US$ 6- 6.5).

Artisanal Small Scale Mining (ASM) in the Ingessana Hills varies somewhat between villages, with some identifying an active participation in the activity and others a decline depending on season and gold-bearing quartz vein discoveries.

Around Gugub village, activities on primary ore were suspended after a spectacular gold discovery of a small gold-rich quartz vein in September 2003 at Khor Gidad 7 km to the north. GRAS geologists report that ~500 miners (officials said 6,000) rushed chaotically into the area from Gugub and elsewhere, and extracted ~56 kg of gold in a week’s time.

According to our interviews and observations it appears that intensive use of mercury in the area is quite recent (around 3 years and maybe less) and is mainly developed at Gugub where gold was first discovered and at Khor Gidad after the gold rush. The other sites mentioned in the sociological reports (i.e. Turda, Khor Neiwi) are alluvial types, without mercury use and presently abandoned.

During our mission, Gugub and Khor Gidad were the only ones in activity, Khor Gidad as an extraction and processing site and Gugub as only a processing site. However, a few isolated women continue to work occasionally on ancient quartz overburden and tailings around Gugub (Abu Djal quartz veins).

The village of Gugub is the most important one with around 170 households (Illustration 3). Primary ore is usually transported to Gugub where families of miners are living and where merchants sell mercury in their shops. The Khor Gidad mining site is located too far from Gugub (around 7 km by track) to allow daily ore transportation by hand and around 70 families from Gugub have started to build new huts in Khor Gidad (Illustration 4). Seven shops selling mercury were identified in each site.

4.2.2. Mining practices

Mining practices are described in the sociological survey (Khalil. A. El Medani, 2003 and Ibrahim, 2003).

Artisanal gold mining in Gugub is practiced by both Dawala and Ingessana tribesmen without legal titles. Most individuals mine and process the ore in small groups, basically as a family affair. The procedures used by local people are representative of very poor people using simple and traditional practices. During our stay, most of the activities were performed by women (13-35 years old), including the hard tasks of digging and excavation. Women represent more than 50% of the labour force; in the rainy season this can reach as much as 90%, as the men go planting (Ibrahim, oral comm.).

The miners do not comply with the provisions of the Mines and Quarries Act (1972). Given the adverse situation created by civil strife around the Kurmuk and Queissan border areas in 1996, and in an effort to develop the sub-sector in a sustainable way, the Government tried to legalise gold mining in southern Blue Nile and elsewhere by granting special licenses. A few mill owners introduced hammer mills into the area in 1997-1998, but authorities soon drove them out. Although the known gold occurrences in the Ingessana Hills are relatively small and scattered, in 1999 a private investor obtained an exclusive prospecting license for gold exploration and mining in a 10 km^2 area around Gugub from the Ministry of Energy and Mining, but for the adverse reasons surrendered the area. A condition imposed by the Government in such deals is the strict compliance of artisanal gold miners with mining alluvial gold only.

Today, the area is open for licensing without any restrictions on the artisanal gold mining activities. The only restriction imposed by Government is the introduction of rock mills into the area (Ibrahim, 2003).

In the area, two different types of gold mining are found: mining of alluvium and colluvium, and mining of gold-bearing quartz veins.

Mining of alluvium and colluvium

The exploitation of alluvial ores will not be detailed in this report in as far as:

- it does not require the use of mercury;
- it is already described in the sociological report;
- no exploitation of this type was observed during our mission.

Alluvial mining is done during the rainy season only. Ore excavation from alluvial terraces in the different khor and wadis takes place in the vicinity of the villages and implies only small groups of 10-20 peoples. The estimated average daily amount of alluvium extracted from pit by a male miner is about 0.5 ton.

The process involves the following steps:

- Site preparation and removal of overburden;

- Digging of the pit for excavation of the alluvium;
- Panning of the ore;
- Hand recovery of gold specks and nuggets from heavy-mineral concentrates.

Alluvial-type gold produced in the area goes directly to the market without further purification (Ibrahim, 2003).

Mining of gold-bearing quartz veins

Mining of gold-bearing quartz veins was the only type we observed during the field mission.

(1) Ore extraction, digging and ore selection on the site

Miners noticed that ore is richer at the footwall of gold-bearing quartz lenses and consequently the quartz is generally totally extracted. Miners also work with eluvial material and altered wall rock. In the first metres, extraction is done mainly by women in a rather muddled way without mechanical tools (Illustration 6). Men are only involved in mining at greater depths. Wildcat digging and excavation are common. Digging tools include the rudimentary axe, pick, and shovel. Sledge hammers and chisels are used mainly in hard-rock excavation (Illustration 6). Miners do not use explosives.

The shafts are up to 15-20 m deep, dug every 3-4 m, and are interconnected and barely timbered.

The material is manually hoisted and visually sorted in an empirical way in order to try to concentrate the most probable gold-bearing material. Artisanal primary gold mining thus entails visual selection of mineralised rock pieces (Illustration 6). The largest pieces of quartz are burnt overnight to facilitate hand-crushing and manual milling.

The estimated average daily amount of gold-bearing quartz rock extracted from a pit by a male miner is about 20-30 kg.

At this stage, the selected ore (Illustration 6) is transported to the “family unit“ at Khor Gidad or, more commonly, at Gugub.

Illustration 6 - Women mining activities at Khor Gidad quartz veins area

(2) Crushing, milling and panning at home

Manual crushing and milling, and panning are done by women in the yard of the family unit in the shadow of huts or an awning. Rock grinding is done with a grindstone or steel mortar (Illustration 7). The semi-final quartz+gold powder (200-500 microns) is panned by women.

The grinding capacity (to <0.074 mm) is less than 5 kg/day/individual. Miners can crush and grind more eluvial material and altered host rock than quartz.

Illustration 7 - Grinding with steel mortar (a) and grindstone (b)

No-one mentioned quartz-powder storage. Crushing, grinding and then amalgamation are performed in one daily sequence.

Panning is done manually in excavated pools using traditional wooden pans. The tailings are dumped around the huts outside the “family units” (Illustration 8). Panning efficiency with the traditional wooden pan is ~50%. Apparently, all fine gold grains remain in the light fraction of the tailings. A panning test on waste material, done during the field mission, showed common gold specks.

Illustration 8 - Panning area in Khor Gidad producing an large quantity of tailings around the huts and “family units”

(3) Amalgamation at home or in the shops

After crushing and/or milling, the pan concentrate is sent home or to the shops for amalgamation. In the Gugub artisanal gold-mining sites, mercury is used in extraction of fine gold particles from the panned concentrate.

The way of handling mercury in gold amalgamation is unsophisticated (Illustration 9 & Illustration 10). After a last panning in the enclosure (Illustration 9a), Hg is poured onto the concentrate with water and mixed with bare fingers to make the amalgam (Illustration 9b).

Illustration 9 - Gold recovery process phases (a) Panning; (b) Amalgamation by hand; (c) Squeezing with piece of cloth; (d) Roasting on frying pan

After thorough mixing, the amalgam is squeezed through a piece of cloth and the excess Hg is recovered for reuse (Illustration 9c). The miners collect the amalgam by hand, taking no precautions at all. After that, the remaining amalgam is transferred to an open plate or frying pan for roasting (Illustration 9d). In the private yard there is no specific place for amalgamation. Commonly, owners indicated to us two or three different places located along fences or at the shadow of awnings (Illustration 10).

Illustration 10 - Amalgamation performed without precautions in the "family units"

(4) Roasting at home or in the shop

The gold amalgam is roasted in mobile bonfires that facilitate the movements outside or inside huts. It is especially the men who practise the roasting.

Daily, they roast the amalgam without taking any precautions. The roasting operation can occur (Illustration 17):

- In the village close to the dealer's shop where they buy mercury;
- In the yard of the "family units";
- In the huts (usually the ones dedicated for cooking).

The miners place the gold amalgam on a steel plate and burn it in a bonfire until they consider by visual experience that the *"doré"* is ready (Illustration 11 & Illustration 34). The diameter of amalgam burned during the demonstration carried out during our visit ranged from 3 to 8 mm. We expect that the duration of the burns (~10 minutes) is too short and the temperature produce by the bonfire is too low to burn all the mercury. Roasting tends to be incomplete and at least 15-25% of the *"doré"* contains residual mercury (Illustration 11). The *"doré"* also contain other metals accompanying gold in the ore (lead, iron, copper).

Illustration 11 - Example of amalgam before roasting (left) and "doré" (right) after roasting

(5) Recycling of waste and tailing in pools

The phases of grinding, amalgamation and roasting generate tailings, residues or waste, often dumped near the zones of operation. In or around enclosures or even gardens, waste heaps are common that can be several cubic metres in size. Test panning of this type of material or of soil near working zones again showed the presence of gold specks and of occasional drops of mercury, especially in Gugub.

Workers indicated that during the rainy season part of these tailings and residues are sometimes panned in pools located in the Khor Alyas close to the southern entrance of Gugub village. Heavy-mineral concentrates are then amalgamated and roasted again at home. Tailings recycling could be done many times in order to recover residual gold.

(6) Water supply

One of the main local problems is the lack of water in mid summer. Water is provided and bought by Ingessana women and children that bring the water from about 2 km away (Ibrahim, 2003). They carry a pair of 4-gallon plastic containers on their shoulder with the aid of a stick as a yoke, or on their heads (Illustration 12). The eight gallons of water cost S.D. 50 (US$ 0.2).

Illustration 12 - Water supply from wells assumed by women and children

4.2.3. Gold production and use of mercury

Gold production from quartz-vein mining

It was very difficult to evaluate the quantity of gold produced from alluvium without the use of mercury, and from quartz vein with mercury amalgamation. We only estimated the production of gold from the exploitation of the gold-bearing quartz veins that require the use of mercury.

Quartz-vein mining is dangerous and difficult work compare to alluvial mining. In a shear zone, gold distribution is erratic and commonly needs detailed geological and mineralogical studies to be well understood. Some miners discover this new aspect of artisanal mining and sometimes appear to be disappointed. They do not have the required skill and experience to mine quartz lenses, and the mining area is a succession of old and new wildcat holes with quartz overburden strewn around.

Several parameters indicated that only 30 to 50% of the gold contained in the ore may be recovered during the complete process and therefore by the miner:

- The large amount of quartz abandoned on site;
- Visual selection of the best samples on site without hand lenses;
- Incomplete manual grinding;
- Loss of gold during panning;

- Loss of gold during the amalgamation process.

The sociological study and the interviews carried out during our mission gave some indicative data to try to evaluate the quantity of gold produced and of mercury used during the artisanal gold-mining on the Gugub sites:

- The workers said that one worker produces 0.5 to 1 g Au/day. The production is organised by family and the production of one worker must be considered as the production of one family. Sociological studies indicated that around 350 adults are of an age to work in the two villages. We assumed that there were 200 to 300 families working for about 300 days per year. Taking into account this information, the quantity of gold produced ranged from 100-300 g Au/day and 30-90 kg Au/year.
- The dealers said that they buy 5-10 g Au/day. The number of dealers identified in the area ranges from 15 to 20. Taking into account this information, the quantity of gold produced is 75-200 g Au/day and 22.5-60 kg Au/year.

  These estimates were based on two independent sources that gave similar results. Workers and dealers probably underestimate their production and actual values may be higher.
- Extraction capacity does not exceed 20-25 kg/day/worker and the manual grinding capacity is probably less than 5 kg/day/worker. All adults of an age to work cannot produce at the same time 25 kg of ore from their mining activity and grind 5 kg of it. Persons are needed for separate tasks. In this case, Illustration 14 indicates that to produce 100 g Au/day from the Gugub sites, the workers involved must be 800 and the gold grade 30 g/t, whereas to produce 300 g Au/day workers involved must be 1,000 and gold grade 72 g/t. Gold analyses carried out by GRAS on Gugub quartz veins (Elnour K. Mohamed *et al.*, 2002) indicated that such average grades are unrealistic. The gold analyses carried out on 53 quartz chip samples ranges between 0 and 14.8 g/t with only 7 values exceeding 1 g/t (1.10; 1.45; 1.72; 1.90; 2.3; 4.04; 14.8).

The annual artisanal gold production estimate for Gugub sites over the period 1997–2002 is 450 kg Au/year (Ibrahim, 2003), but we demonstrated that the 350 individuals working in Gugub cannot produce the quantity of gold indicated:

- Hypothesis 1: a large part of the gold sold during the dry season (probably 50%) comes from alluvial production;
- Hypothesis 2: a large part of the gold sold during the dry season (probably 50%) comes from gold reserves made by workers during the rainy season;
- Hypothesis 3: the number of miners working in the area is underestimated;
- Hypothesis 4: gold production estimates are historical rather than actual.

Illustration 13 taken during our mission (dry season) militates for hypothesis 1 or 2: the hand of the gold dealer is full of alluvial gold nuggets instead of "*doré*" pellets coming from roasting. The production of gold from the exploitation of the Khor Gidad gold-bearing quartz veins that require the use of mercury represent only a part (30% ?) of the production of gold in the area. The evaluation of mercury consumption must take into account these precious information.

Illustration 13 - Gold “reserve” shown by a dealer

A	B	C	D	E	F
Daily Production of gold (Au g/day)	Gold Grades (Au g/t)	Daily quantity of ore extracted needed (kg)	Number of Miners needed (production = 25 kg/day/workers)	Number of Workers involved in Crushing needed (production = 5 kg/day/worker)	Total number of workers needed
		(A/B) * 1000	C/25	C/5	D+E
100	1	100000	4000	20000	24000
	5	20000	800	4000	4800
	10	10000	400	2000	2400
	15	6667	267	1333	1600
	20	5000	200	1000	1200
	25	4000	160	800	960
	30	**3333**	**133**	**667**	**800**
	50	2000	80	400	480
	70	1429	57	286	343
300	1	300000	12000	60000	72000
	5	60000	2400	12000	14400
	10	30000	1200	6000	7200
	15	20000	800	4000	4800
	20	15000	600	3000	3600
	25	12000	480	2400	2880
	30	10000	400	2000	2400
	50	6000	240	1200	1440
	72	**4167**	**167**	**833**	**1000**

Illustration 14 - Estimates of number of workers and Au-grades necessary to produce 100 to 300 g of gold a day from gold-bearing quartz veins in the Gugub area

Mercury consumption

The sociological study and the interviews carried out during our field mission give some indications for evaluating the amount of mercury consumption during artisanal gold mining processes in the Gugub sites:

- Mercury is only used to recover gold from primary ore. We demonstrated that gold produced from primary ore is probably 100-150 g/day and 30-45 kg/year. The ratio of Hg lost per Au produced is usually estimated at 1.5. Following this ratio, the quantity of Hg lost per year is 45 to 67 kg. In this figure the use of mercury is around 250 g Hg per household of artisanal miners per year.
- The dealers said that they sell 2-4 g Hg/day/worker. On the basis of 200-300 families involved, the quantity of Hg used per year is 200-360 kg. Based on this figure, the use of mercury is around 1000 g Hg per household of artisanal miners.
- Taking into account this information, the Hg lost/Au produced ratio is probably over 3 in the Gugub area. It seems very high as the miners use Hg just in the final concentration step and Hg is not quite available in the region (M. Veiga, pers. com.). Following this ratio and an annual gold production from quartz-bearing quartz vein of 30 to 45 kg Au, the quantity of Hg used per year is 90 to 135 kg. Based on this figure, the use of mercury is around 450 g Hg per household of artisanal miners.

According to Ibrahim (2003) the annual loss of mercury to the environment was 675 kg, but his estimate was based on the wrong consideration that all annual gold production (overestimated at 500 kg/year) comes from quartz-vein mining. We demonstrated above that this is apparently not the case in Gugub district.

We identified three possible sources of mercury loss:

- Wrong manipulation of mercury at the shop or at home;
- Loss of Hg on the ground or in tailings during the amalgamation phase;
- Evaporation during the roasting phase.

According to our field observations and the estimations performed, the annual use of mercury in the Gugub district ranges between 250 and 500 g Hg per household of artisanal miners.

5. Methodology

5.1. SAMPLING STRATEGY

After the orientation survey covering the selected area, the following points were analysed:

- Where are the main sources of mercury pollution of artisanal gold mining in the area, considering that the sites visited are representative of this activity?
- What are the main pollution vectors that could transfer the mercury towards a target?
- What are the main target(s) exposed to the direct or indirect effects of mercury?

This analysis enabled us to classify the visited sites according to their specific features, and their representativeness of the main local and regional risks arising from artisanal mining activity in this area.

The artisanal gold miner families and the 10 to 15 local gold-merchant shops in Gugub and in Khor Gidad constitute the same broad mercury hotspots. There is no plan of the villages of Gugub and Khor Gidad. The location of the “family units” of the miners is not exactly known.

As in Zimbabwe (Billaud and Laperche, 2003) and Laos (Laperche *et al.,* 2004), the sampling strategy followed a risk-assessment approach, considering the various sources of pollutants, their transfer and pathways, and the potential targets. The following table summarises the field observations (Illustration 15).

Analysis of the system has lead to reinforce sampling in the villages, and particularly in and around the huts of artisanal gold miners and more generally in and around the "enclosed family units" that group several huts of the same family. The main targets identified are local people. Potential risks to the ecosystem were considered to be minor in this process.

It was then decided to focus sampling on the following media (Illustration 17):

	Items Considered	Level of occurrence
SOURCES	• Hg storage in shops	✱✱
	• Accidental Hg spill during amalgamation (huts & shops)	✱✱✱
	• Amalgam roasting in huts	✱✱✱
	• Waste dispersal	✱✱
	• Contamination of sediments during panning on residues in Gugub	✱
TRANSFER & PATHWAYS	• Household dust contamination	✱✱
	• Hg vapour dissemination contaminating huts and their environment	✱✱✱
	• Soil contamination in the vicinity of contaminated huts	✱✱✱
	• Sediment transportation	✱
	• Transfer to the biological chain (fish)	✱
HUMANS TARGETS	• Hg inhalation during roasting	✱✱✱
	• Household dust and soil ingestion (mostly children in huts or yards)	✱✱✱
	• Contaminated dry maize and sorghum consumption	✱✱
	• Fish consumption (rare)	✱
	• *Contaminated poultry consumption*	not considered in this study

Illustration 15 - Main components of the risk analysis

Sampling locations in Gugub and Khor Gidad villages

- *Top soil*: potentially submitted to ingestion by local people, mostly children and poultry. Sampling was focused around the huts of artisanal gold miners, in the yard of “family units”, and in the main square of the village (school, mosque).

- *Tailings hills:* Composite grab samples were taken from tailings hills around “family units” and in vegetable gardens.

- Some *termite hills* located in amalgamation zones, in gardens or inside huts were tested in order to check if termites can concentrate Hg during hill building.

Location Type	Number	GUGUB				K. GIDAD				TAGA			
		Total	Yard	Hut	Shop	**Total**	Yard	Hut	Shop	**Total**	Yard	Hut	Garden
Family units (miners)	Spot	10	9	8		7	7	4					
	Samples	35	21	14		25	20	5					
Shops and family unit combined	Spot	2	2	2	2	5	5	3	2				
	Samples	13	7	4	2	21	16	3	2				
Gardens	Spot	6				3							
	Samples	11				3							
Mining area	Spot	2				5							
	Samples	3				6							
Reference	Spot	2				3				1	1	1	1
	Samples	4				3				4	2	1	1
TOTAL	Spot	15	11	10	2	17	12	7	2	1	1	1	1
	Samples	66	28	18	2	58	36	8	2	4	2	1	1

Illustration 16 - Distribution of samples (soil, dust, termite hill, tailing) by spots and type of location in the 3 villages.

- *Household dust*: as amalgam roasting occurs in some huts, dust was sampled in selected huts.

- *Airborne dust:* Hg contents in atmosphere were measured outdoors for background evaluation and indoors (huts) under different conditions (see below).

- *Wadi and khor stream sediments*: the first objective of the sediment sampling was to control Hg mobility in the drainage pattern around the villages as well as in the main collector Wadi Maganza. The strategy was adapted to field conditions; sediments were taken mainly along the narrow streams as possible; we collected either sand (in stream beds) or silty black sediments (on stream banks).

Fifteen soil and seventeen dust sampling spots were selected in Gugub and Khor Gidad villages. Details are given in Illustration 16.

The spots sampled for the environmental study are identified on the sketch maps of each village (Illustration 18 and Illustration 19).

Based on information from the sociological survey, reference houses were identified in each village: school and mosque yard in Gugub and recent "family units" outside the mining area in Khor Gidad. The selection criteria were based on the lack of artisanal mining activity for the concerned household.

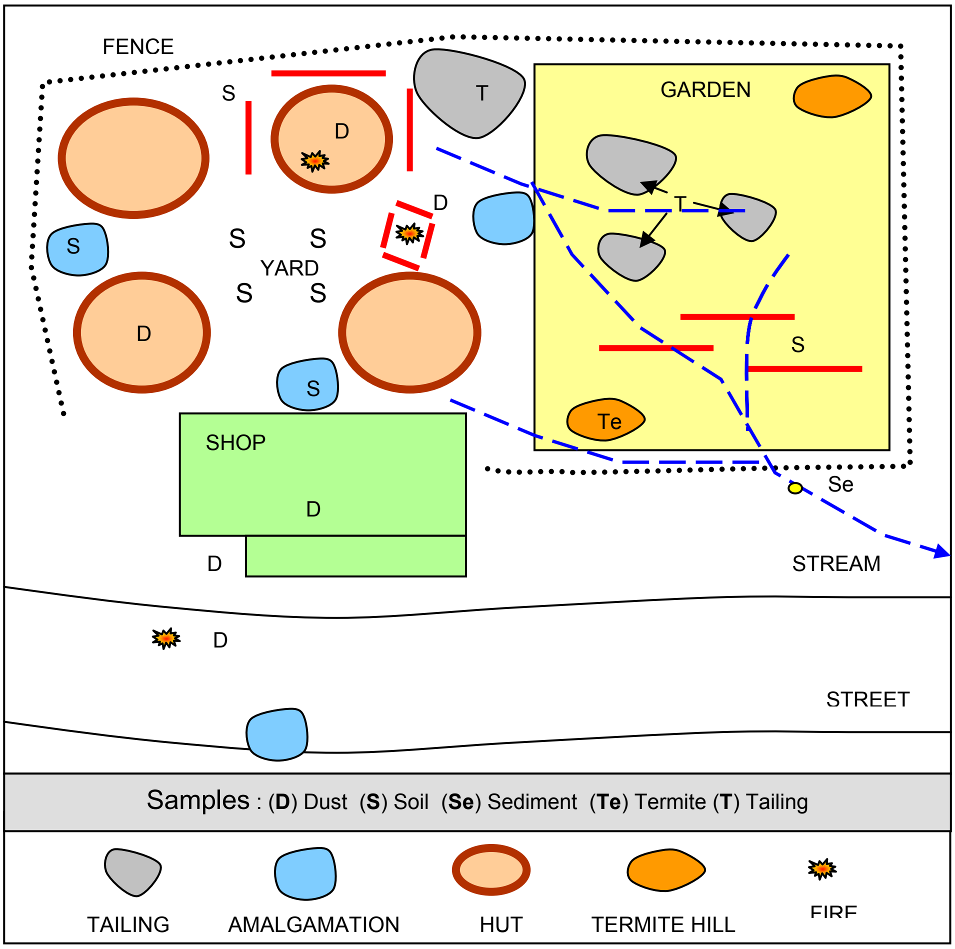

Illustration 17 - Sketch map of the sampling strategy applied in the villages

- ***River system***

  - **Stream sediment**

As mentioned by Suleiman (2003), the extent of mercury pollution from artisanal gold amalgamation in Gugub and Khor Gidad villages could be controlled by surface run-off. The villages are located on a high relief and rugged hillsides with a steep dendritic drainage system. As a result, high-energy soil erosion characterises the area during the rainy season (600-800 mm). Although the general drainage pattern of the Ingessana Hills is radial, steep ravines draining Gugub and the surrounding artisanal gold mining sites coalesce to the northeast to join Wadi Maganza, which drains the north-eastern parts of the Ingessana Hills into the Blue Nile some ~45 km to the northeast (Illustration 20 & Illustration 22).

Wadi Maganza waters contain artisanal gold mining waste/tailings washed off from Gugub and the mining sites. Among these products, mercury is expected to move ahead with Wadi-fill (clay, silt, sand, gravel) along Wadi Maganza up to the Roseries dam reservoir at a point ~20 km south of Ad Damazin (Illustration 2).

The objective of the sediment sampling was oriented to control Hg mobility in the drainage pattern around the villages Gugub and Khor Gidad and in the main collector Wadi Maganza. (Illustration 18, Illustration 19, Illustration 23)

As said above, where possible we collected either sand (from stream beds) or silty black sediment (from river banks).

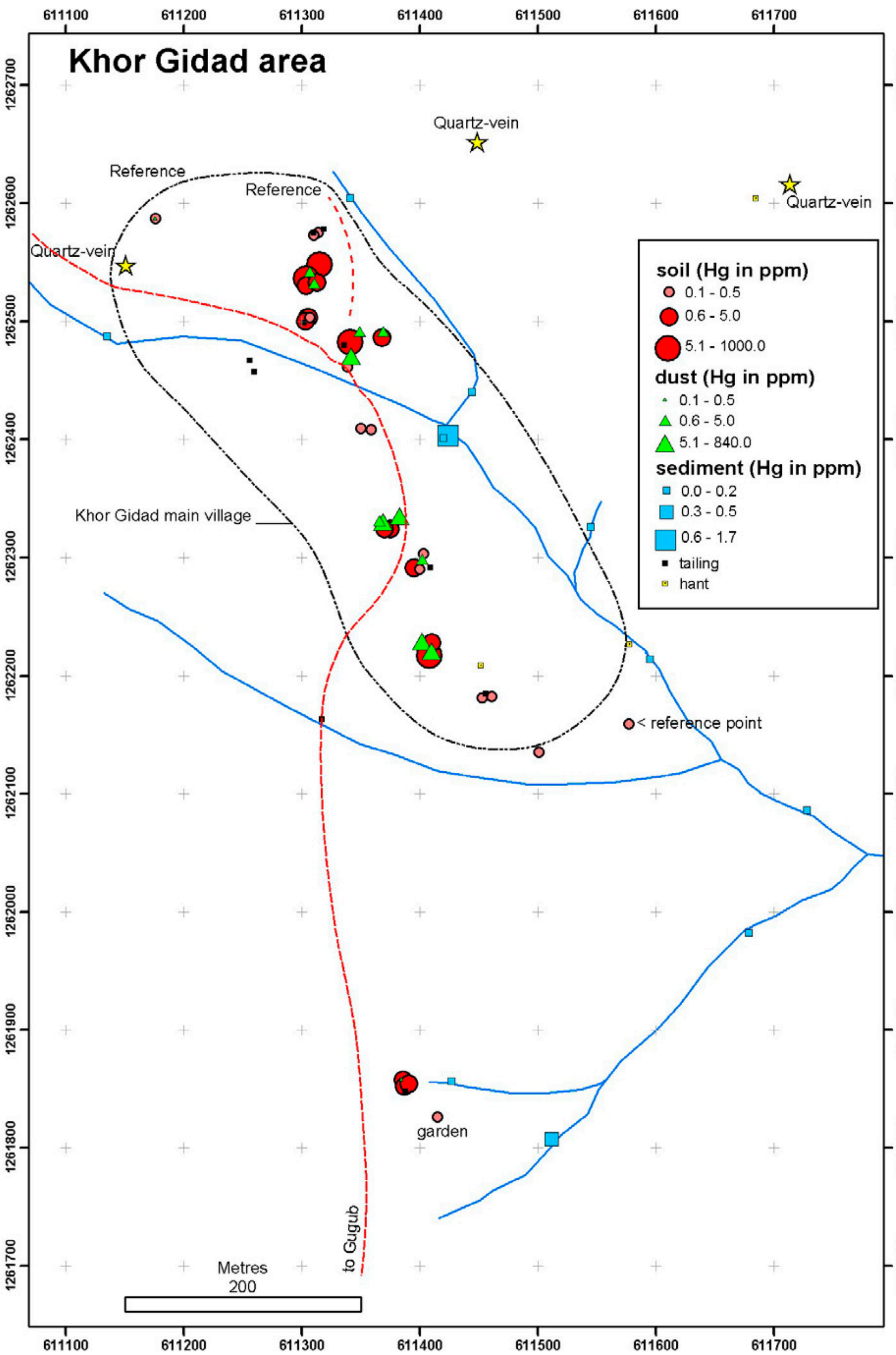

Illustration 18 - Sketch map of Khor Gidad area with location of samples and results of Hg analyses (N.B.: "hant" = "termite hill")

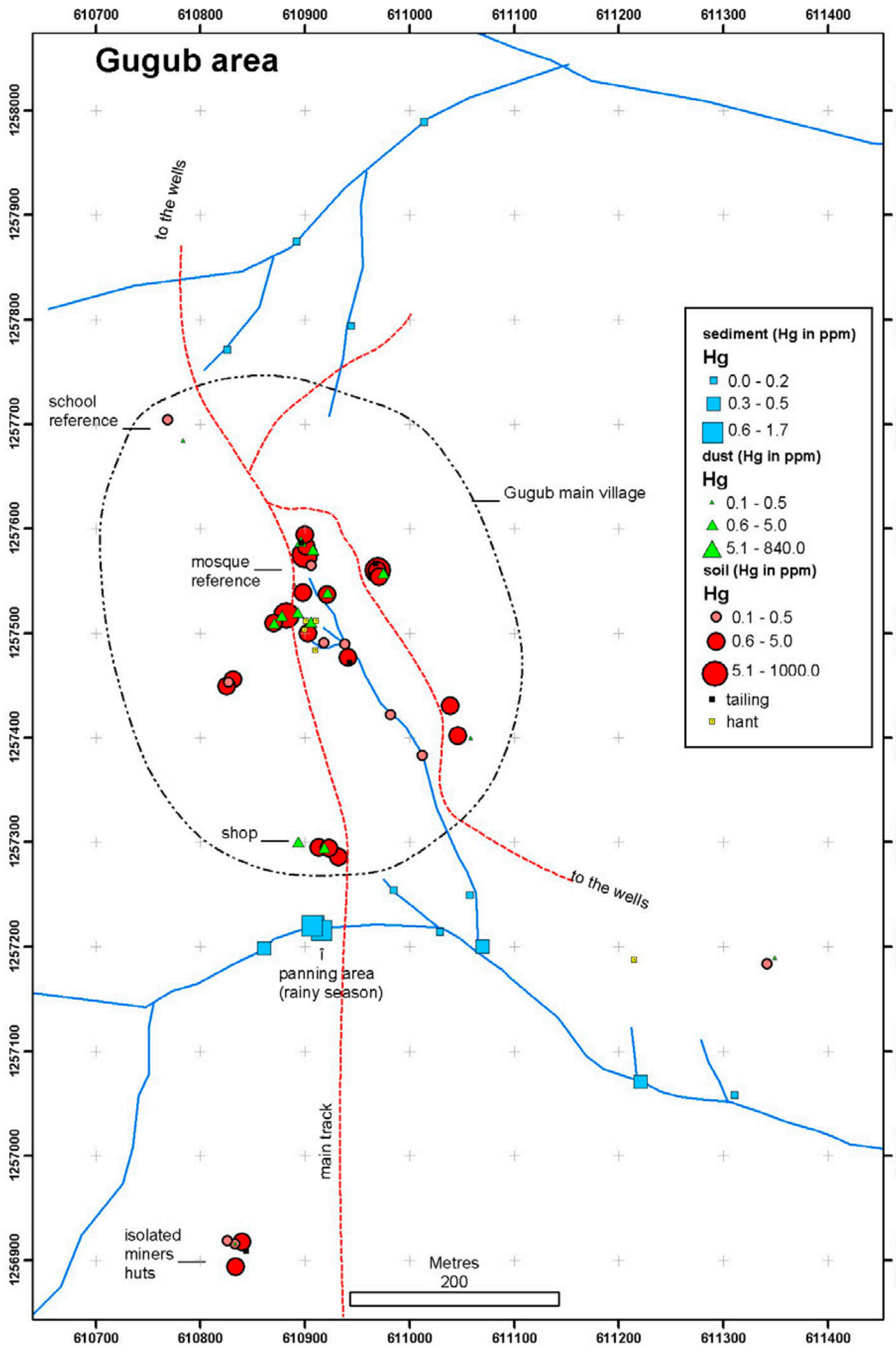

Illustration 19 - Sketch map of Gugub area with location of samples and results of Hg analyses (N.B.: "hant" = "termite hill")

- **Fish**

According to the Protocols for Environmental & Health Assessment of Mercury Released by Artisanal and Small-Scale Gold Miners (ASM) (UNIDO, 2003), the fish sampling strategy was as follows:

- Identify the target species based on interviews with local people, fishermen, fish markets and, if possible, in consultation with local or regional experts;
- Identify areas for fish sampling, including both upstream and downstream of mining activities and, if possible, reference areas;
- Identify sampling areas that coincide with geographic areas identified as "environmental hot spots".

We had particularly unfavourable sampling conditions in the Gugub and Khor Gidad area: Wadi Maganza and its tributaries had dried up completely making it impossible to catch any fish in this area.

The sociological study also indicated that fish are consumed only occasionally and mainly dried. Fishing is an occasional occupation mainly practised by the younger generation. According to local people and the Sudanese participants, the Roseires reservoir was the only site where we could find fish of different species and size, as requested by the protocol.

Fish sampling was carried out in the Roseires reservoir due to the lack of fish elsewhere in the selected area. The aim was to test contamination of the Nile at this location, but not to interpret Hg release issued from the Gugub area.

Despite these drawbacks, we managed to take some samples from two sites:

- (i) In the Roseires reservoir (fishing spots 1, 2 and 3), about 50 km east of Gugub: the reservoir is fed by water from several watersheds, some of which were affected by gold-mining activities that predated those at the site originally selected and which were probably on a larger scale, such as ~12 km east of the Blue Nile bank at Belguwa-Sakatna, sites ~80 km southeast of Ad Damazin. Mercury input may also come from other artisanal gold-mining sites within the river catchment as far as Qeissan some 150 km to the south. This reservoir was built in 1965 and covers a total area of about 400 km^2. A large number of fishermen catch fish here, mainly using nets, especially in the part farthest from the dam. Most of the fish is sold outside the fishing zone, in Khartoum). The dried fish consumed in the Gugub area is mainly brought from Ad Damazin and the Roseires reservoir.
- (ii) In a part of the river that contained a small water hole (fishing spot 4 –Illustration 21), we carried out a fishing campaign and were able to catch several species of fish. Once again, this site was not directly connected to the gold-washing zone and the village of Gugub.

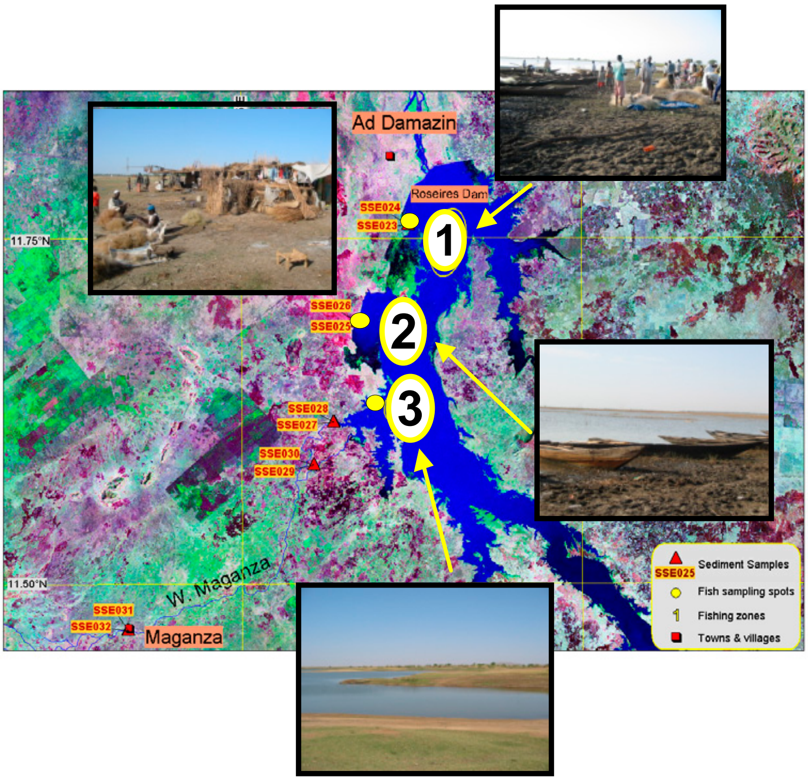

Illustration 20 - Location of the three fish sampling spots in the Roseires reservoir.

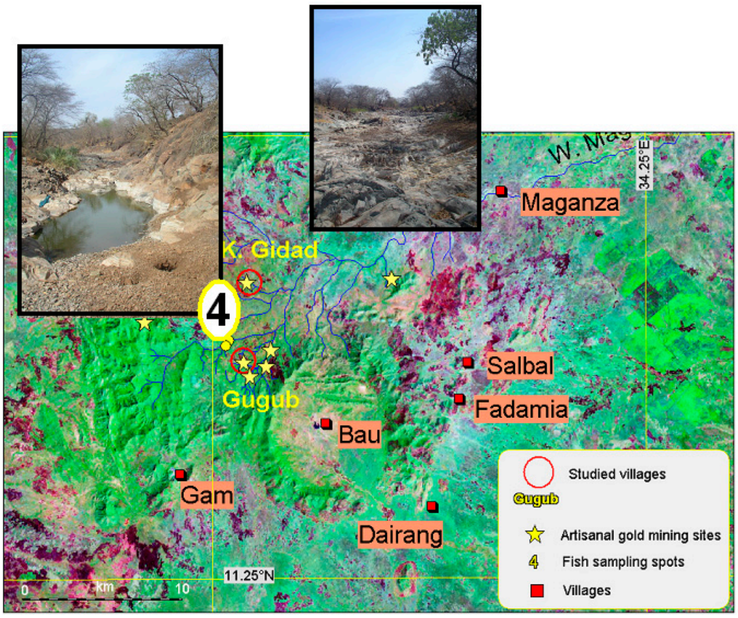

Illustration 21 - Location of fish sampling spot N° 4 in a hole in a small dried-up river, north of Gugub.

Analysis of the results relating to the level of mercury contamination in fish must necessarily bear in mind the constraints imposed by sampling conditions and the absence of any direct relationship with the gold-mining site and the village of Gugub. Nevertheless, they show the current state of mercury contamination in fish in this part of Sudan, especially around the dam that lies downstream of several gold mining sites.

At the four fish-sampling spots, catches were made by local fishermen using nets.

Fifteen different species were collected, with a total of 108 individuals (Illustration 22). The 15 fish species collected are shown in Appendix 5.

	Reservoir			**River**	**TOTAL**
Sampling spot	**1**	**2**	**3**	**4**	
Species number	**8**	**3**	**7**	**4**	**15**
Fish number	**37**	**15**	**23**	**33**	**108**

Illustration 22 – Summary of the fish collected in the reservoir and the river.

5.2. SAMPLING PROCEDURES

Sampling procedures are described in detail in the field report (see Récoché *et al*., 2004). The following table illustrates the distribution of samples per village and locations (Illustration 23).

Location	**Gugub**	**K. Gidad**	**Taga**	**Maganza**	**Roseires**	**Total**
Soil	32	31	3			**66**
Termite mounds	5	3				**8**
Tailings	6	11				**17**
Dust	16	13	1			**30**
Air Monitoring	4	1				**5**
Sediment	26	13		6	4	**49**
Fishes		33			75	**108**
Vegetables	6		2			**8**

Illustration 23 - Distribution of samples by media.

5.3. ANALYSIS OF SAMPLES

5.3.1. Analysis of solid samples

The Lumex RA-915$^+$ analyser equipped with the RP 91C attachment (Illustration 24) is intended for measuring mercury in solid samples. Its operation is based on differential Zeeman atomic absorption spectrometry using high-frequency modulation of light polarisation.

A radiation source (mercury lamp) is put in a permanent magnetic field. The mercury resonance line λ = 254 nm is split into three polarised Zeeman components (π, σ- and σ+). When radiation propagates along the direction of the magnetic field, a photo detector detects only the radiation of the σ- component, one of those falling within the absorption line profile and another one lying outside. When mercury vapour is absent in the analytical cell, the radiation intensities of both σ components are equal. When absorbing atoms appear in the cell, the difference between the intensities of the σ components increase as the mercury vapour concentration grows.

The principle of the RP-91C attachment is based on the thermal destruction (at approximately 800 °C) of a sample matrix and reduction of the bound mercury in the sample, followed by a volatilisation and a determination of the amount of elemental mercury formed by the RA-915$^+$ analyser.

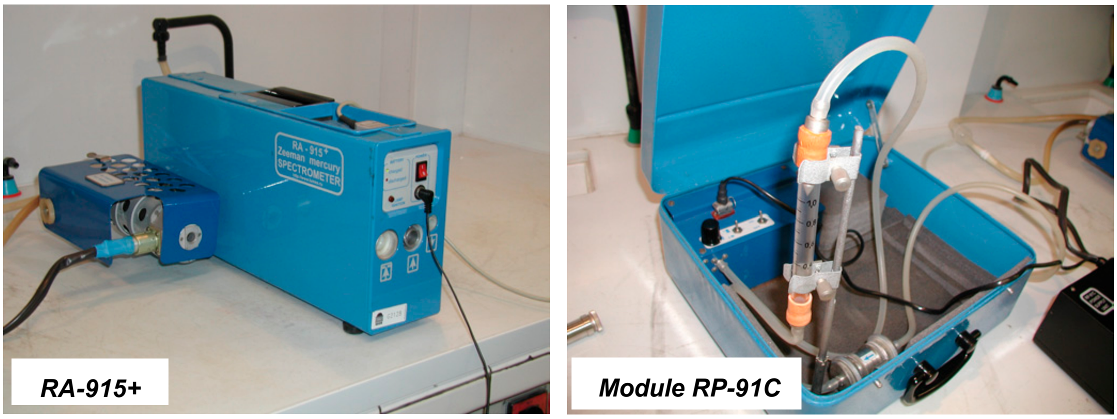

Illustration 24 - The LUMEX RA-915$^+$ analyser equipped with the RP 91C attachment.

The quantification limit is 0.01 mg kg^{-1}. For concentrations above 20-30 mg kg^{-1} a specific single-path cell is used in place of the multiple-path cell. After stabilisation of the RA-915$^+$ lamp and of the pyrolysis attachment (about 40 minutes), the equipment was calibrated with two reference materials (NIST 2711 and CANMET STSD1). A sample (20 mg to 300 mg) is placed in a quartz spoon and inserted in the oven. The signal is automatically acquired through monitoring software on a laptop computer linked to the Lumex RA-915$^+$. The RA-915$^+$ analyser does not differentiate between mercury forms; it yields a total mercury concentration. Accuracy of the method was checked every ten samples by analysing a reference material (NIST 2709). 10% of samples were analysed twice with the Lumex; 10% of results were confirmed by analysis with a reference method.

Before analysis, samples were dried (40 °C) and then ground at 80 µm. Results are given in mg kg^{-1} dry weight.

Quality-control procedures are summarised in appendix 7.

5.3.2. Air monitoring

The Lumex RA-915$^+$ analyser without the pyrolysis attachment (Illustration 24) is intended for measuring the mercury-vapour concentration of ambient air, both in a stationary and continuous mode.

After switch-on, it takes about 20 minutes to stabilise the light source. When the measurement mode is started, a zero adjustment is first carried out automatically. Then the analyser measures and continuously indicates the measured mercury concentration of the gas as both a numerical value and a graphic chart.

The detection limit and flow rate are respectively given by the manufacturer at 2 ng m^{-3} and 20 L mn^{-1}. The multi-path cell should not be operated for too long in rooms with high mercury vapour concentrations (higher than 10,000 ng m^{-3}).

Currently, there is no easily available methodology for measuring mercury levels in ambient air. The RA-915$^+$ analyser (Lumex) needs external calibration for precise validation of air mercury analysis, but such calibration was not possible before this mission. Absolute values given by the Lumex for mercury concentrations in air should therefore be considered cautiously.

5.3.3. Analysis of fish

Before sampling the fish meat, standard length[3] and body weight were measured on each individual and each was photographed. A small piece of dorsal skeletal muscle (1.5 x 1.5 cm) was cut out and kept in a formalin solution (10% in deionised water) in 50 mL plastic bottles. Caps were tightly screwed and covered with Parafilm. Preliminary experiments in our laboratory have shown no significant differences

[3] Standard length: from the nose to the caudal fin basis.

between total Hg concentrations, expressed on a dry weight basis, in muscle samples obtained by this procedure and in frozen samples[4].

All analyses were performed in the "Laboratoire d'Ecophysiologie et Ecotoxicologie des Systèmes Aquatiques" (LEESA), run by CNRS and the University of Bordeaux, France.

Total Hg concentrations in fish muscle samples were determined by flameless atomic absorption spectrometry. Analyses were carried out automatically after drying by thermal decomposition at 750 °C, under an oxygen flow (AMA 254, Leco-France). The validity of the analytical method was checked during each series of measurements against three standard biological reference materials (TORT-2, lobster hepatopancreas; DORM-2, dogfish muscle; and DOLT-2, dogfish liver, from NRCC-CNRC, Ottawa, Canada). Hg values were consistently within the certified ranges (Illustration 25).

Detection limit (DL) for total Hg was based on three standard deviations from blank measurements: DL on a dry weight basis was 1.4 ng g^{-1}. Method precision (relative standard deviation, percentage RSD) of total Hg determinations, estimated from 5 replicates of fish muscle samples, was 5%.

All fish muscle concentrations were reported on a dry-weight basis (40 °C over 2 days).

		TORT-2	DORM-2	DOLT-2
Total Hg	**Certified value**	0.27 ± 0.06	4.64 ± 0.26	2.14 ± 0.28
(µg g^{-1})	**Measured value**	0.27 ± 0.04	4.78 ± 0.33	2.08 ± 0.12

Illustration 25 - Comparison of measured and certified values of total mercury concentrations using three standard biological reference materials

5.3.4. Analysis of vegetables

Vegetable samples were cleaned several times with ultra pure water to remove solid particles. Samples were dried at 40 °C during 3 days and then ground to less than 2 mm. Between 0.1 and 0.2 g of dried samples were digested at 90 °C during 24 h in closed Teflon bottles with 6 ml aqua regia. The samples were then diluted to 50 ml with ultra pure water.

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[4] This preservation procedure was set up during the first stage of the "Mercury in French Guiana" research programme, since in most of the sites studied there was no electricity supply and biological samples could not be frozen on site. A comparative study was done over a 4-month period, using fish muscle samples collected from one individual (N=60) and stored at –20 °C, or in diluted formalin at room temperature and at +35 °C. Replicates were collected after 1, 2, 4, 8 and 16 weeks. No significant differences were observed between Hg total concentrations (P<0.05), expressed on a dry-weight basis, for the different storage conditions.

Total mercury was analysed by atomic fluorescence after reduction with tin chloride. The system used is the Merlin analyser from PSA, which is composed of a continuous flow system, a gas–liquid separator purged with argon, and an atomic fluorescence detector. Measurements were controlled by the PSA software. The reductant solution was 5% m/v $SnCl_2$ in 15% HCl. The standards were prepared from 1000 ppm mercury solution (MERCK). Working standards were prepared by diluting stock standards. The matrix of working standards is adapted to the matrix of digested samples. Typical calibration was in the range of 0-500 ng L^{-1}.

Accuracy of calibration is checked with a different stock solution (PANREAC). Spiking of the samples before digestion controlled the whole analysis. Samples were diluted 10 times before analysis.

In order to evaluate mercury deposition on vegetables hanging in huts where roasting takes place, the first few millilitres of water used for cleaning the vegetables was kept for analysis. The volume of solution used was approximately 40-50 mL. The solutions were digested and then analysed following European standard EN13506 (water analysis by atomic fluorescence).

6. Results and interpretations

6.1. SOILS

According to our results described in the previous sections, the most probable sources of soil contamination are apparently related to:

- Atmospheric deposition of mercury during roasting and the dissemination of household dust around artisanal miner huts. We sampled the top soil from 0 to 2 cm depth, about 2 m away from the hut walls. Samples were taken along a 3-4-m-long lines (Illustration 26). The soils were thus sampled on different sides of the hut in order to evaluate the level of contamination in the vicinity of the artisanal miner huts.
- Solid deposition of mercury during the amalgamation process. We collected composite surface soil samples (0 to 2 cm depth) in the yards of “family units”, around usual amalgamation sites or roasting-bonfire sites. The procedure (Illustration 26 & Illustration 17) consisted of taking three to six samples that were thoroughly mixed to form a composite sample. The laboratory analyses were done on a sub sample of the composite as for the exterior hut samples.
- Composite top soil samples were collected in the school yard, in the mosque yard of Gugub village, as well as in a recent “family unit” outside the mining area in Khor Gidad, considered as a reference point to evaluate the geochemical content farther away from the source of Hg emissions.
- Composite surface soil samples (0 to 2 cm depth) were also collected for evaluation of Hg contamination in different gardens close to amalgamation zones. Samples were taken along a 3-4-m-long lines cross-cutting superficial drainage (Illustration 17).

Illustration 26 - Soil sampling phases – (a) Digging along line or point; (b) Sieving; (c) Sample splitting; (d) Collection in bottles

Results of Hg analyses are reported in Appendix 6.

Illustration 27 & Illustration 28 show the distribution of Hg contents in soil for each of the villages and show the average level of Hg content in the different location in each village:

- The “natural” geochemical background given by analyses in Taga village and in other reference location spots in Gugub ranged from 100 to 150 ng g^{-1}.
- The average geochemical content in the villages of Gugub and Khor Gidad are around ten times higher than the local background. Medians range from 1213 in Gugub to 640 ng g^{-1} in Khor Gidad.
- Higher values in the two villages (up to 10^6 ng g^{-1} in Khor Gidad and up to 27,626 ng g^{-1} in Gugub) are related to amalgamation zones where Hg droplets were visible after panning (Récoché *et al.,* 2004). The amalgamation zones show values several times higher than in other places where values are close to the local background.
- The average contents in the gardens range between 130 to 280 ng g^{-1} in Khor Gidad and Gugub respectively, and are close to the background level. However, the

values in Gugub are higher than in Khor Gidad, which could be considered as a quite recent mining area.

- The point values are higher in Khor Gidad than in Gugub, but the average background is higher in Gugub.
- The school yards show background Hg contents (106 ng g^{-1}) higher than soils sampled around houses of artisanal miners (Illustration 28).
- In Khor Gidad, the higher contents are found in the soil around the shops, where amalgamation may be common and quickly performed without precautions, and around the huts of dealers. In Gugub practices seem different, with a high content in shops but also and mainly in the yard around huts of miners.

Location	Village	N	Min.	Max.	Med.	Mean	SD
Amalgamation site	Gugub	13	275	27,626	2,585	4,273	6,894
	K. Gidad	14	283	1,000,000	1,740	85,442	257,295
Garden	Gugub	6	133	675	217	283	185
	K. Gidad	2	114	151	133	133	19
Reference	Gugub	3	83	648	106	279	261
	K. Gidad	3	100	1,345	602	682	511
	Taga	3	90	148	110	106	12
Yard	Gugub	9	430	4,966	1,716	2,116	1,437
	K. Gidad	11	100	3,328	240	763	1,000
Total	Gugub	31	83	27,626	1,213	2,488	4,830
	K. Gidad	30	100	1,000,000	640	40,230	180,784

Illustration 27 - Average Hg content in soil (in ng g^{-1}) (N: number of samples; Min.: minimum value; Max.: maximum value; Med.: median; SD: Standard Deviation)

Near the mining site at Khor Gidad, the miners do their last panning and the amalgamation close to the mercury dealer shop. We measured high Hg values near these places. In the village of Gugub, the final panning and amalgamation are performed more commonly in the “family unit” and mostly in the yard between the huts where we noted high values in soils.

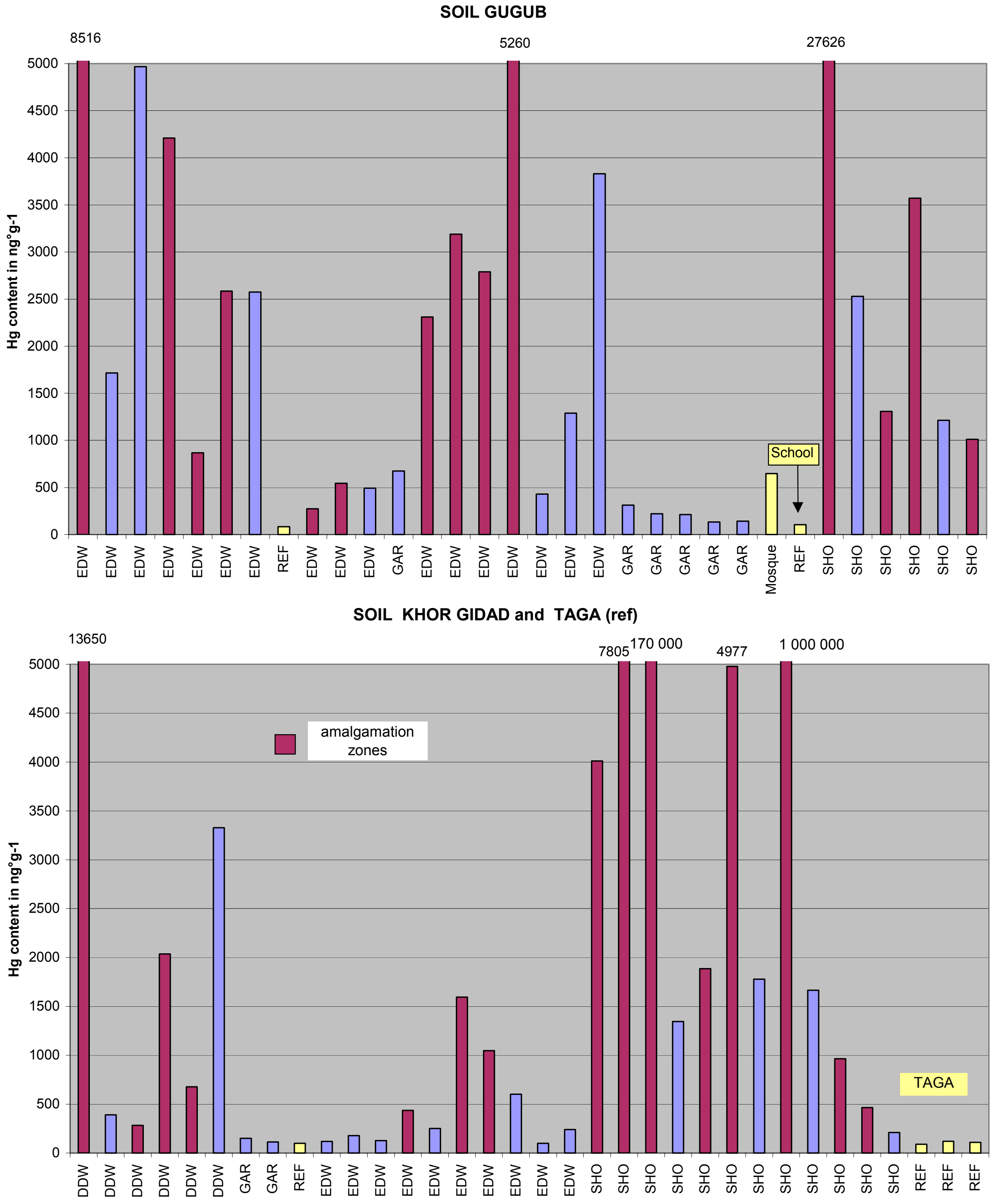


Illustration 28 - Average Hg content (in ng g^{-1}) in soils in Gugub, Khor Gidad and Taga villages [reference yard (REF), "family unit" of dealer (DDW), "family units" of miners (EDW), shops and associated family unit (SHO), and garden (GAR)]

Several spots that were initially considered as reference in the Gugub and Khor Gidad villages, present higher Hg values than the background recorded at the reference village of Taga. These values show mean values that are too high for reference sites in the table of illustration 27. At Khor Gidad, it is a soil sampled in a miner's hut (SSO052) and in a shop's backyard (SSO029). These sites were said not to have been the object of amalgamation or roasting phases. Hg contents of the two samples are respectively 600 and 1,345 ng g^{-1}. These results show indirect ground contamination from surrounding processing sites.

At Gugub, the Hg content of the soil sampled in the school yard (106 ng $g^{-1)}$ is equivalent to the background. However, the soil sampled at the mosque's entrance, where it can be assumed that no amalgamation or processing operations took place, shows Hg contamination (648 ng g^{-1}) (Illustration 28). The school is located at the northern extremity of the village, whereas the mosque lies at the village centre, in the middle of huts and in front of a shop, which could also explain and underline an indirect ground contamination around the gold recovery centres.

6.2. DUST SAMPLES

Depending on the information given by owners, dust sampling was carried out in different places:

- Inside huts where roasting was performed frequently;
- Inside huts that never were used for roasting, in the same "family unit";
- Inside huts in Taga for control;
- Inside shops where frequent mercury exchanges and amalgamation are performed;
- Outside huts in the yard where families and especially children stay around roasting or close to amalgamation spots.

By asking questions it was rather difficult to identify what was the main roasting place. In Khor Gidad, outdoor roasting seems to be the norm. In Gugub, however, It seems that the proportion is approximately 50% outdoors and 50% indoors.

The grounds of each hut were brushed to collect dust (Illustration 29). As a control, we collected sometimes two bulk dust samples per enclosure in different huts. After splitting, the grab samples were collected in a 150 mL double-capped plastic bottle. Domestic dust samples were sieved in the laboratory at 500 µm (to eliminate pieces of charcoal, wood, hairs, etc.) and analysed with the Lumex RA915^{+}.

Illustration 29 - Dust sampling in a hut.

Results are summarised in Illustration 30 & 33 and in Appendix 6.

	Total	GUGUB	KHOR GIDAD	TAGA
Number	29	15	13	1
Minimum	52	52	123	183
Maximum	840,000	2,751	840,000	183
Median	1,433	1,219	3,177	183
Mean	46,860	1,236	103,094	183

Illustration 30 - Average Hg content in dust per location type (in ng g^{-1})

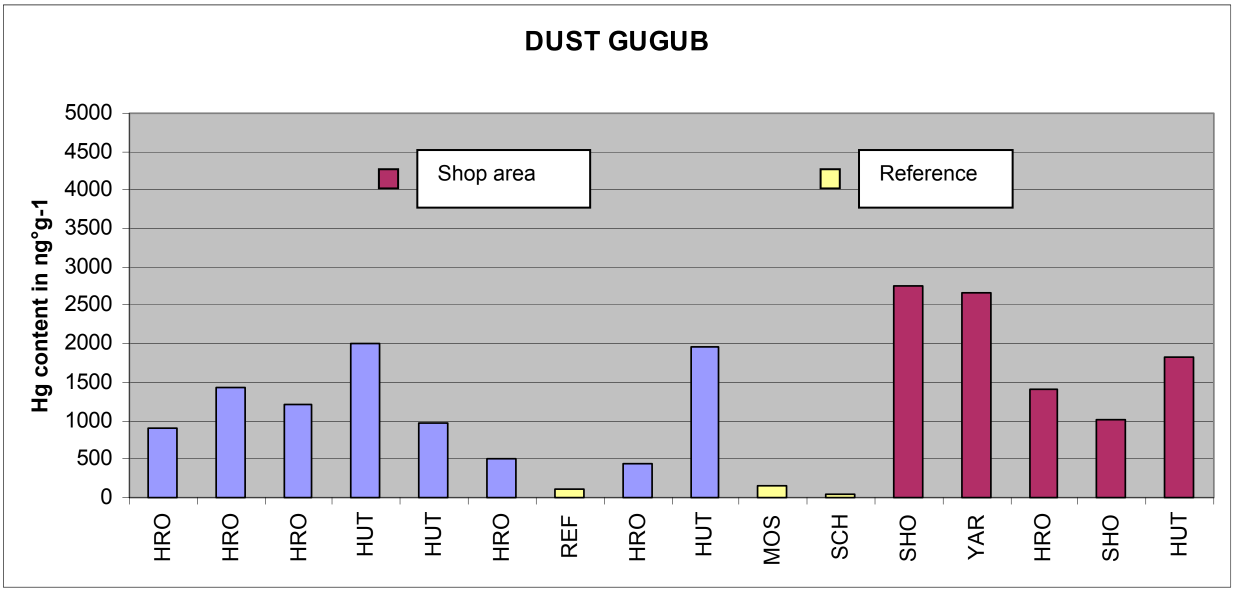
In the reference spots (REF) the Hg contents are low and range between 52 (school of Gugub) and 183 ng g^{-1} (hut in Taga). The contents are the same as those of the soils taken there (110 ng g^{-1} in Taga). This homogeneity shows that domestic dust is not particularly enriched in regard to natural soil.

In Gugub, the Hg contents in dust collected in various places are rather homogeneous. They range between 500 and 2,760 ng g^{-1}, these values are several times higher than the background of reference spots. The values do not depend particularly on the sample location (inside a hut with or without roasting, yard between several huts, floor of dealer's shop). The Hg contents in dust of huts where roasting takes place are close to those of huts never having been the site of roasting.

The Hg contents in dust from Khor Gidad range between 123 and 840,000 ng g^{-1} and are higher than those of Gugub (<2,760 ng g^{-1}). The highest Hg contents come from dust taken on the ground of trade shops (465,000 and 840,000 ng g^{-1}). Nuggets effects are possible.

As in Gugub, except in the shops, there is no preferential distribution of the high values according to sample location. The information supplied by inhabitants can be vague, but these results show that the contamination is quite general and homogeneous at the scale of the villages. Average contents show significant contamination of domestic dust in some huts and yards of artisanal miners. It is clearly demonstrated that indoor amalgam roasting will significantly contaminate the dust in huts, but there are no major differences between the Hg contents in soils compared to Hg contents in dusts throughout the village.

It is not surprising to find higher values in Khor Gidad where during our mission mining activity was more important and essentially concentrated on quartz vein mining, contrary to Gugub where the activity, at that time, was less intense and mainly without use of mercury. However, such contamination may be a long-lasting effect: in Gugub, where artisanal mining is less intense, dust contamination is still present.



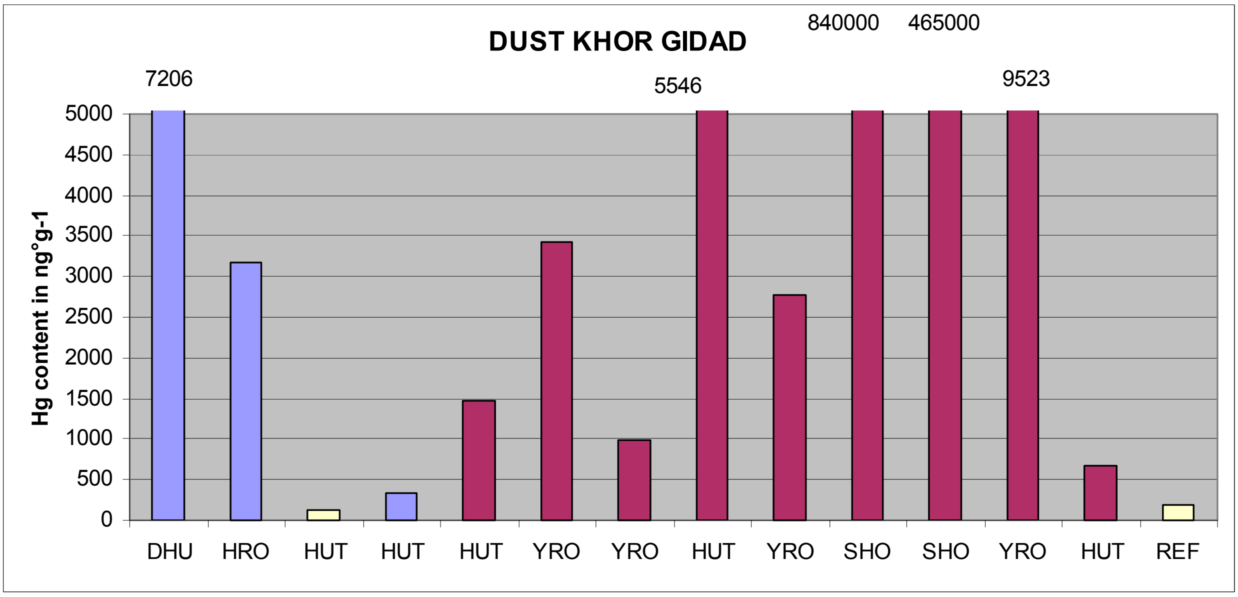


Illustration 31 - Average Hg contents (in ng g^{-1}) in domestic dust per village in: (HUT) Hut; (HRO) Hut with roasting; (YRO) Yard with roasting; (MOS) Mosque; (SCH) School; (SHO) Shop; (REF) Reference spot; (DHU) Hut of Dealer

6.3. OTHER SOLID SAMPLES

6.3.1. Tailings and residues

Composite grab samples were taken from tailings hills around enclosures. Sampling protocol was the same as for soils: sieving to pass 2 mm, splitting, collection in a 150 mL double-capped plastic bottle.


Illustration 32 - Sampling of tailings (left) and termite hills (right) around mining areas and villages

In both villages of Gugub and Khor Gidad the Hg contents in tailings are divided in two populations (Illustration 33):

- a main population with value close to the local background and
- a population presenting higher Hg contamination (from 1,550 to 2,630 ng g^{-1} in Gugub) and locally very high (62,300 and 72,500 ng g^{-1} in Khor Gidad).

In both areas, the tailings sampled on mining sites close to pits and trenches (STA004, STA005, ST014 to STA016) presented the lowest values and confirmed that there no mercury was used on the sites. In Gugub, the highest values corresponded to tailings located in gardens (STA003 and STA017). In Khor Gidad, sample STA007 (62,300 ng g^{-1}) is a tailing constituted by ash and amalgamation residues at the border of the main road and sample STA013 (72,500 ng g-1) is a tailing again constituted by ash and amalgamation residues located in the yard of a "family unit".

The difference between these two populations could be related to the proportion of amalgam residues or ash content in the tailings. The high values measured in Khor Gidad tailings could correspond to recent tailings where no phenomenon of superficial washing by rain has taken place. The ancient tailings of Gugub would have undergone such washing, which would explain their lower Hg content and their homogeneity.

These results show a contamination of such tailings that locally can be important. Their number and location in gardens or within the “family units” is a problem to be taken into account in future operations of environmental management in the area.

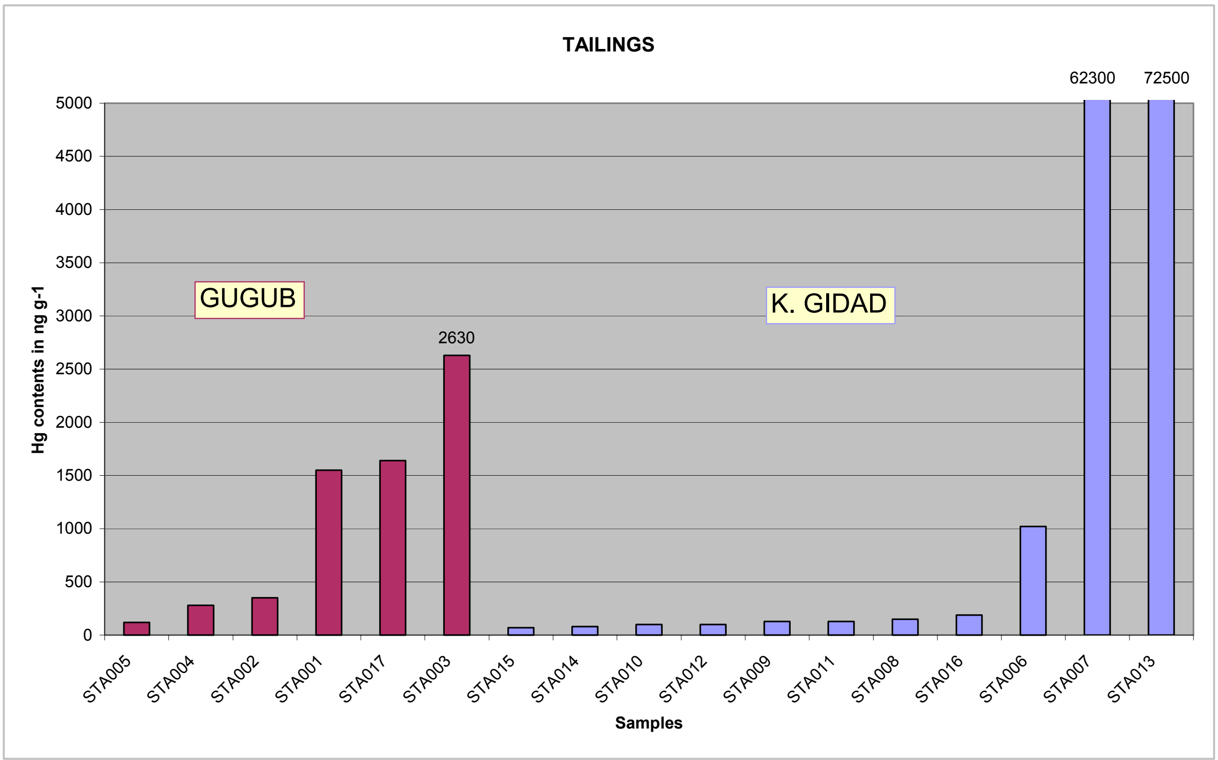


Illustration 33 - Hg contents in tailings in the villages of Gugub and Khor Gidad (in ng g^{-1})

6.3.2. Termite mounds

Large termite hills are scattered throughout the area. Some are located in amalgamation zones, in gardens, or inside huts. We selected eight of them to compare results from soil samples in the same area and to check if termites can concentrate Hg during mound building. The sampling protocol was the same as for soil grab sampling (Illustration 32).

Hg contents are homogeneous and ranged from 28 to 315 ng g^{-1} (Appendix 3 & Appendix 6). The values are close to the background value and indicate that there is no concentration effect associated with termite mounds. Such mounds sampled near soils contaminated by mercury, show relatively lower Hg contents than in the soils.

6.4. AIR MONITORING

6.4.1. Methodology

The two sites studied during this mission have been Gugub, the main village of the area, and Khor Gidad that is rather considered as a working place. The way of using mercury is the same in the two villages: people carry out amalgamation near the huts and then roasting takes place outside or inside the hut, depending on the families. When roasting is done inside, the same fire is used for cooking.

The roasting phase was chosen as the most interesting phase for air monitoring, due to the real possibility of mercury contamination for people during this phase. Moreover, Gugub was chosen for most of the monitoring because it was easier to ask the habitants for a demonstration of roasting. Most of these demonstrations were done by men.

Monitoring was recorded during roasting demonstrations in two typical huts in Gugub and once during a roasting demonstration outside (Illustration 34). In the two huts, dust, soil and some vegetables were sampled as well.

Illustration 34 - Monitoring during roasting (a) Inside a hut in Gugub and (b) Outside at Khor Gidad

Hut A is a typical one: a circular room of 3-4 m diameter, very little aeration and a fire place for roasting and cooking near the wall. The other one, named B, is a more organised hut with a very well delimited place for the roasting fire. The structure of the hut allowed a better evacuation of the smoke due to openings at the junction between walls and roof. This second type of hut is very rare compared to the first one.

In the typical type A hut, the Hg content in dust sampled on the ground is 2,751 ng g^{-1} and in the more organised hut (type B) it is less at 434 ng g^{-1}.

The monitoring aimed at estimating the air quality breathed by the population. For this, the intake hose of the RA-915$^+$ analyser was installed approximately at nose height of the persons involved. During the amalgam roasting phase, the intake hose was placed at the same distance of the fire than the person performing the roasting (around 0.5-1 m from the fire).

6.4.2. Description of results

Roasting in a typical Hut (Type A)

There are four steps during air monitoring of the amalgam roasting shown in Illustration 35: the background situation before roasting, the roasting phase, a step of high mercury concentration after the roasting, and a return to the initial situation.

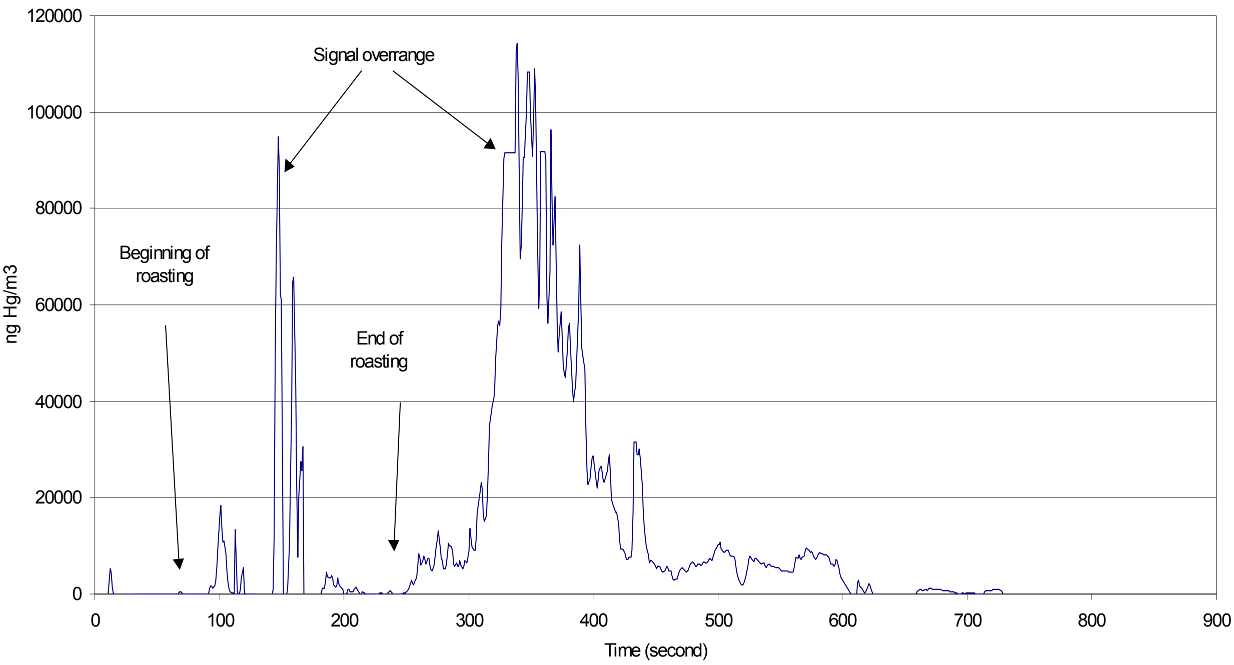


Illustration 35 - Air monitoring in a typical hut in Gugub (type A) before, during and after roasting of an amalgam

During the first step (0-70 s) the fire was already lighted for cooking. The mercury concentration was rather stable (≤200-300 ng m^{-3}). When the roasting starts, the mercury concentration increases very rapidly with a few maximum peak values up to 70-90,000 ng m^{-3} (qualitative value because the Lumex indicated a saturation signal). This step lasted 3 minutes (as the roasting operation in this case) with a period for maximum peaks of less than 30 s. After three minutes the mercury concentration was back to the initial level. The third step occurred after roasting had stopped. This step is characterised by a rapid increase of mercury level in air with maximum values up to 80-100,000 ng m^{-3}. This second period of high levels is longer than the first one (6 mn) and the average mercury concentration is higher than during roasting. The final step is a stable background level.

Two important observations result from the monitoring of roasting in huts:

- The exposure limit for workers exposed to mercury is 25 or 50 µg m^{-3}. This falls within the WHO standards (e.g. 25 µg m^{-3} average air concentration for an 8-hour shift, WHO, 1994), as the period during which high mercury concentrations (around or above 25,000 ng m^{-3}) were detected is 10 mn, which is far below the recommendations of WHO.

- The second peak of mercury concentration is unexpected and more intense than the peak observed during roasting. The first peak is attributed to the volatilisation of the mercury from the amalgam and the second peak is probably due to a late recondensation of mercury aerosols emitted during roasting. The same phenomenon has been observed in air monitoring in Lao PDR (see Laperche *et al*, 2004). This condensation phase indicates that a large part of mercury emitted in the hut remains inside and therefore could accumulate in dust on the floor, on walls, on vegetables hanging in the hut, etc. The second point is that this condensation phase concerned the entire hut, unlike the period of roasting (local evaporation near the fire). All people present in the hut at this moment could therefore breathe this mercury vapour (not only the person near the fire).

Roasting in hut type B

The same four steps during roasting in this type of hut (Illustration 36) can be observed as in Illustration 35. The main differences are:

- A more agitated period (more mercury peaks) during evaporation of the amalgam because of an stirring of the fire by the man who burns the amalgam. This period is longer than in Illustration 35 (around 5 mn from 60 to 360 s). The peak values have the same magnitude (70-90,000 ng m^{-3}) and are very rapid. Nevertheless, the above conclusion concerning average mercury concentrations and WHO recommendations remains unchanged.

- The second peak that we have identified as a possible condensation of mercury aerosols (between 360 and 550 s) is less intense (shorter and lower maximum values) than in hut A. This seems a direct consequence of the good evacuation of smoke in this hut. The problem of contamination of dust, floor, walls, etc., inside this type of hut could thus be less important.

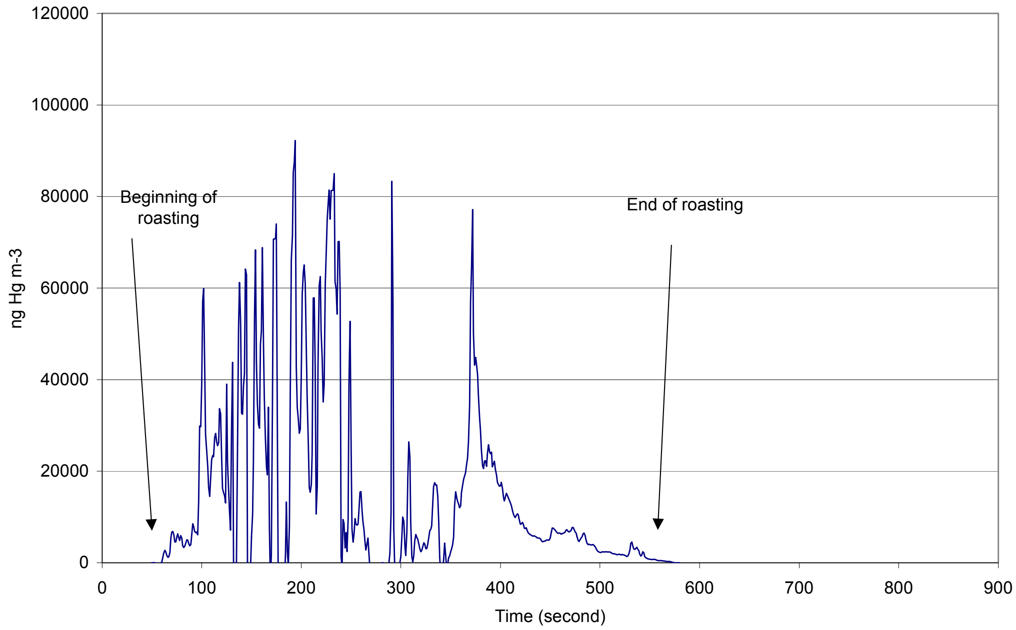


Illustration 36 - Air monitoring in a typical hut in Gugub (type B) before, during and after roasting of an amalgam

Roasting outside

Other roasting operations, which are difficult to evaluate through asking questions of people, took place outside the huts. We estimate that around half of the roasting operations are performed outside. A typical monitoring is presented in Illustration 37. The following five observations can be done:

- A period of squeezing (30-130 s) showed few high mercury concentrations compared with the roasting period (less than about 500 ng m^{-3}).
- As in the hut, during roasting the mercury concentration showed a rapid increase up to 80-90,000 ng m^{-3} (indicative value). The maximum value is approximately the same as in the hut, but the average concentration is lower.
- The duration of high mercury concentrations is shorter than in the hut (around 100 s compared to 500 s in a hut).
- The second peak of probable condensation of mercury vapour observed in the hut is absent in this monitoring.

A re-activation of fire at the end of the roasting showed a residual evaporation of mercury.

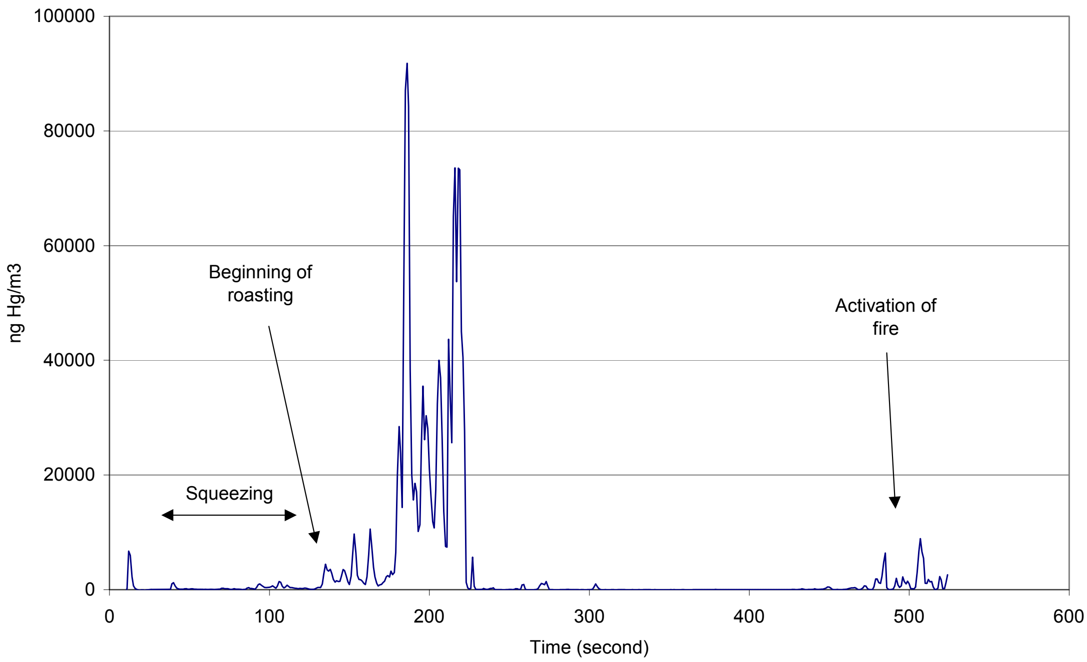


Illustration 37 - Air monitoring in an open place during squeezing, and during the roasting of an amalgam.

6.5. SEDIMENTS

6.5.1. Sampling strategy

Sampling in Gugub, Khor Gidad and Wadi Maganza

Dry stream sediments were collected in the seasonal streams (wadis and khor) around Gugub and Khor Gidad (Illustration 20). We tried to collect samples from the nearest mercury hot spots (upstream) to the main collectors (downstream). The samples were collected in the stream bed with shovels, smoothly mixed, sieved to pass 2 mm, split, and stored in 150 mL double-capped plastic bottles. The sample location was determined with a GPS system and the nature of the sample (from gravel to silt) was noted.

Grab samples rich in humid organic matter were collected, without sieving and splitting, from fishing pools in Gugub and in a pool located in Wadi Maganza close to where it joins the Roseires Reservoir.

Sampling in Roseires reservoir

Wet samples were collected from two fishing sites in the Roseires Reservoir (Illustration 20). Silty sediment rich in black organic matter was collected with a shovel on the banks and stored in 150 mL double capped plastic bottles.

A total of 49 sediment samples was collected: 26 in Gugub tributaries, 13 in Khor Gidad, 6 in Wadi Maganza, and 4 on Roseires reservoir banks. The main data on sediment samples are given in Illustration 38. The complete list is given in Appendix 4

Sediments		**Gugub**	**Gidad**	**Roseires**	**Maganza**	**Total**
Number of samples		26	13	4	6	**49**
Number of spots		20	11	2	3	36
Sample location	Stream	24	10	0	3	37
	Bank	2	3	4	3	12
Area Types	Panning area	8	5	0	0	13
	Fishing area	2	0	4	0	6
	Mining area	2	0	0	0	2

Illustration 38 - Main data on sediment sampling

6.5.2. Description of results

In the mining area, mercury contents ranged from 42 to 1,649 ng g^{-1} on a dry weight (dw) basis in Gugub stream sediments, and between 48 to 886 ng g^{-1} (dw) in the Khor Gidad stream. In Wadi Maganza and the Roseires reservoir with flowing water, values are lower: mercury contents ranged from 42 to 148 ng g^{-1} on a dry weight (dw) basis in Wadi Maganza and between 157 to 386 ng g^{-1} in the Roseires reservoir. Most of the samples displayed concentrations <400 ng g^{-1} in Gugub and Khor Gidad as summarised in Illustration 39.

The respective distributions are presented in Illustration 40.

Sediments	Gugub streams	K. Gidad streams	Wadi Maganza	Roseires reservoir
Number	25	13	6	4
Mean	308	196	75	250
Median	160	118	66	228
Standard deviation	416	220	35	88
Maximum value	1649	886	148	386
Minimum value	42	48	42	157

Illustration 39 - Summary of the Hg concentrations observed in Gugub, Khor Gidad, Wadi Maganza and Roseires reservoir sediments (in ng g^{-1}, dry weight)

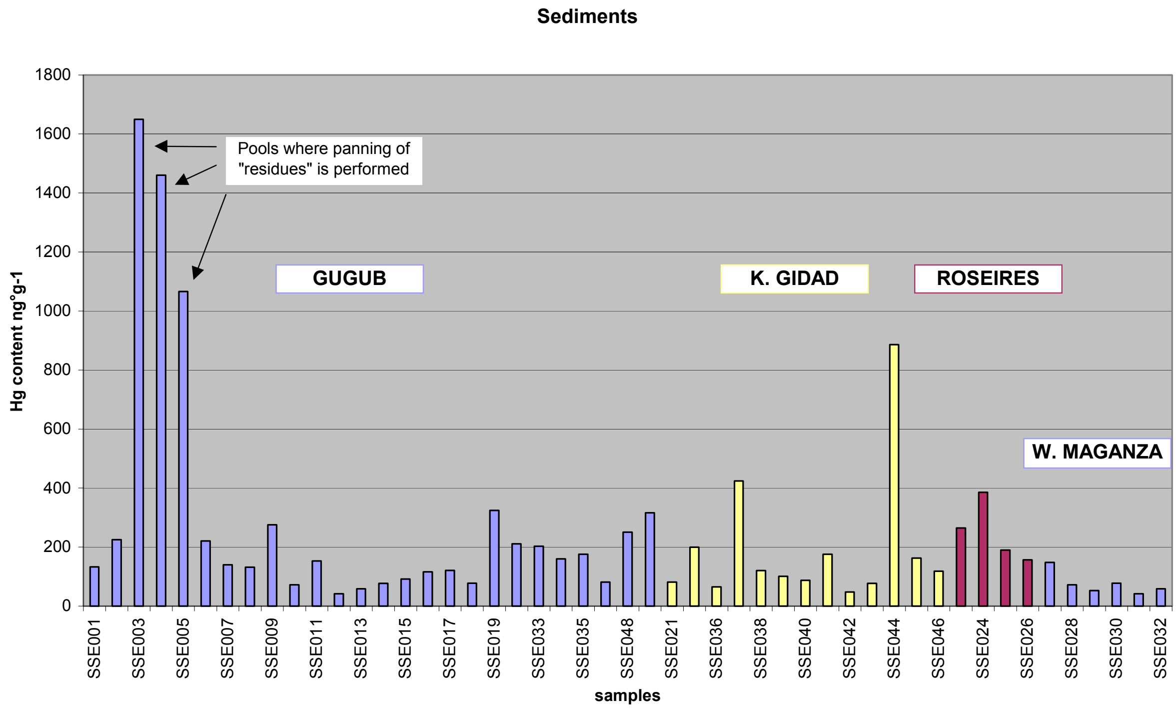


Illustration 40 - Distribution of mercury concentrations in Gugub, Khor Gidad, Wadi Maganza and Roseires reservoir sediments.

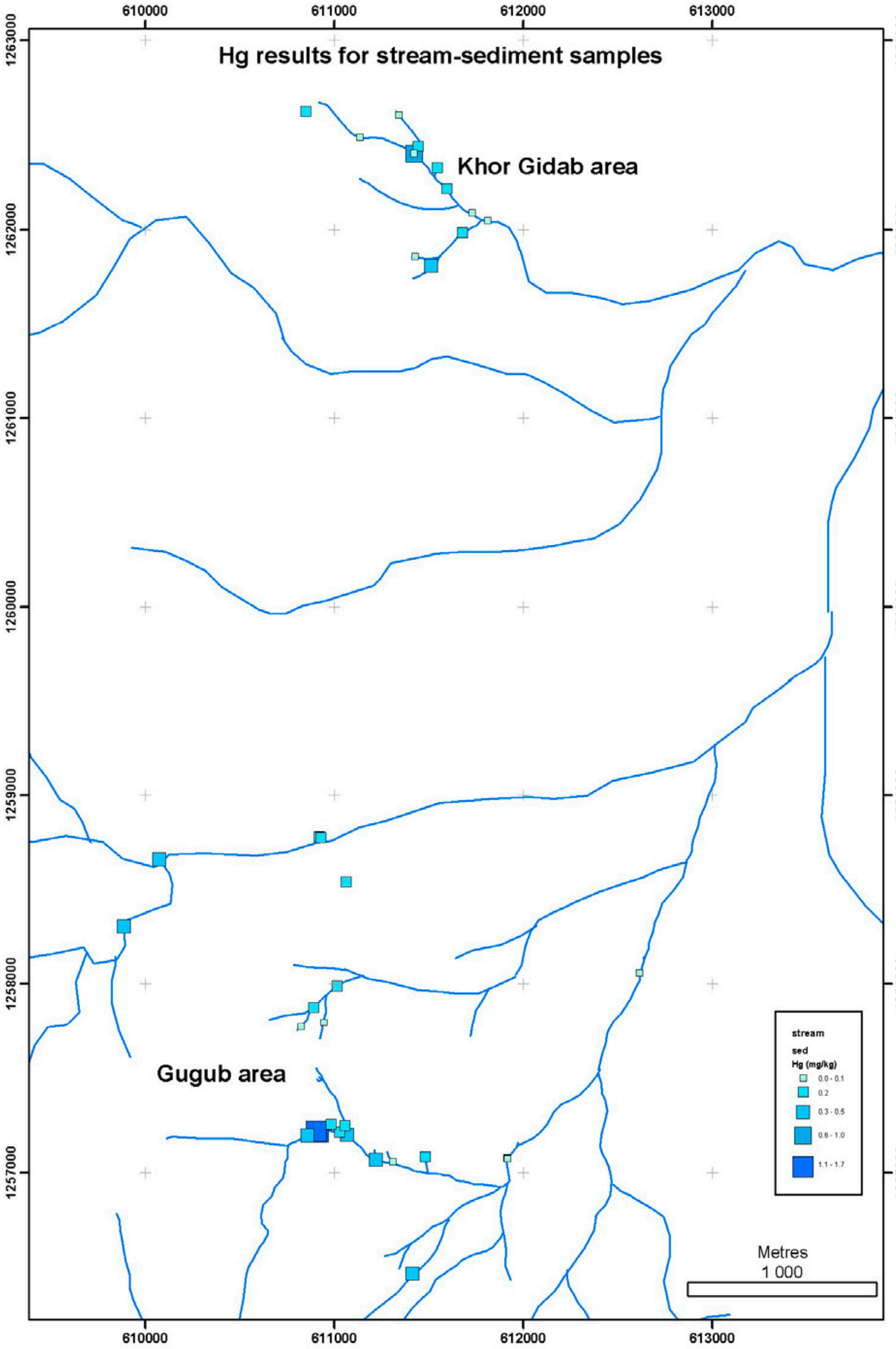


Illustration 41 - Location of Hg analyses results for stream-sediment samples in Gugub and Khor Gidad areas.

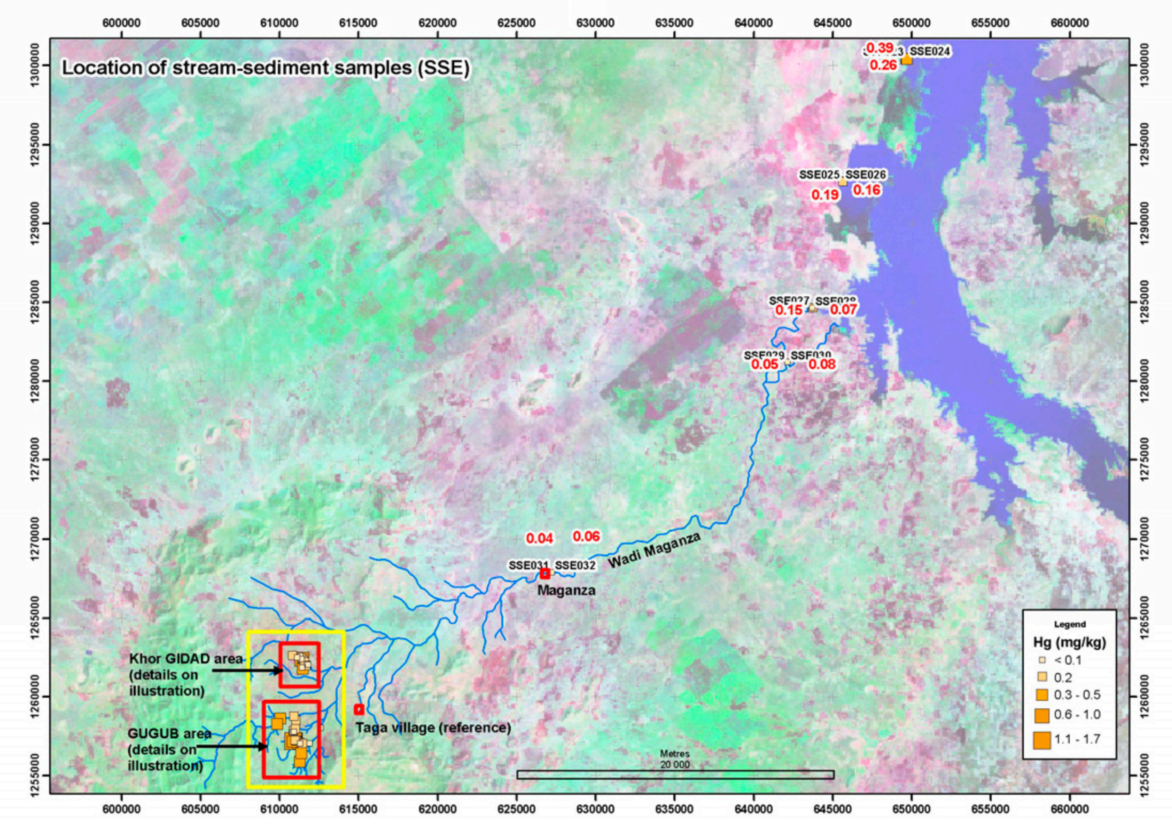


Illustration 42 - Location of stream-sediment samples along Wadi Maganza and at the Roseires reservoir

- The Hg contents in sediments of wadis and khors flowing from the villages of Gugub and Khor Gidad have relatively high contents near the zones of amalgamation (villages); after this, a rapid decrease of Hg contents is seen over some hundreds of metres downstream from the mining villages (Illustration 18, Illustration 19, Illustration 40).
- <u>The Hg contents in sediments of Wadi Maganza are relatively low and do not show high levels of contamination compared to the usual guideline values for sediment management in Europe or America</u> (Illustration 51).
- In the village of Gugub, the high values correspond to sediments taken in the southern network draining most of the surface water from the village where amalgamation took place. The highest values (from 1,066 to 1,649 ng g^{-1}) are located along Khor Alyas where, during the rainy season, part of the tailings and residues are sometime panned in pools (see 4.2.2, Illustration 19 and 40). Downstream is a water well supplying the village with drinking water. North of the village, the network drains only the area of the school and sediments do not show significant Hg contamination.

- In the village of Khor Gidad, Hg contents are mainly below 200 ng g^{-1} (Illustration 40) with two values above (424 and 886 ng g^{-1}) without apparent contamination downstream (Illustration 18).
- The black-organic-matter-rich silty sediment collected on the banks of the Roseires reservoir, presents Hg contents (157 to 386 ng g^{-1}) close[5] to those of contaminated streams from the mining villages, which however are located several tens of kilometres upstream. The reservoir is a sedimentation area, where either the contaminated particles can settle down, or the dissolved mercury can precipitate. The Roseires reservoir located on the Blue Nile collects drainage waters from several artisanal gold-mining activities (Illustration 2) including Wadi Maganza draining the Gugub site. The mercury in the Blue Nile may be released from other artisanal gold-mining sites in activity, such as ~12 km east of the Blue Nile bank at Belguwa-Sakatna, sites ~80 km southeast of Ad Damazin. Mercury input may also come from other artisanal gold-mining sites within the river catchment as far as Qeissan, some 150 km to the south.

It is not possible to compare the results obtained on dry samples from the villages of Gugub and Khor Gidad with samples taken somewhere else in flowing rivers. The sampling conditions (focused on dry samples with organic matter) certainly explain partially the high values encountered. Hg contamination of sediments occurs in the villages where amalgamation and roasting takes places, but seems restricted to a narrow zone of a few hundreds of metres around the villages; at present, no apparent contamination is found downstream in Wadi Maganza.

6.6. VEGETABLES

Some vegetables were sampled in a few huts to evaluate the contribution of these vegetables to the mercury intake of the local population.

The lifestyle of the communities is influenced both by traditional nomadic customs and sedentary habits. They depend mainly on livestock and farming. In Gugub and Khor Gidad, women cultivate maize and sorghum along stream terraces, or in small private gardens close to the huts and Hg-processing spots. The common diet in the Gugub area is based on two meals per day. Sorghum and maize porridge constitute the main meal. During the summer, sorghum and maize are dried in the huts by suspending them from the roof just above the home fires (Illustration 44) until they eventually become black. There is no doubt that these vegetables are exposed to smoke from the fire, with Hg vapours from the roasting phases.

In summer, no fresh vegetables from the mining area are available, so we decided to focus our sampling on the dry maize and sorghum hanging from the roofs of the huts. As we planned to carry out a few vegetable analyses, six samples were collected inside the huts at Gugub, as well as two at Taga for control purposes. Four huts were

[5] Except high value from Khor Alyas.

sampled and two samples taken in each (1 maize and 1 sorghum). Two huts were considered as control: one at Gugub and the other at Taga.

SVG1 to SVG4 are dusty smoked pieces of maize or sorghum hanging from the roof of the huts since October 2003. In these huts, roasting operations are regularly done. SVG5 to SVG8 are pieces of maize and sorghum collected in reference huts in Gugub or Taga (reference village). The last pieces of vegetables were rather clean samples compared to SVG1 to SVG4. The results are given in the Illustration 43 below.

Remark: the quantities of mercury in the first cleaning water are given in ng of mercury (estimation for a 50 mL solution). In order to compare these results, it should be noted that the pieces of vegetables were of equivalent size.

Sample	Location	Type	Remark	Hg content on clean vegetable (mg/kg dry weight)	Hg (ng) in the first cleaning water
SVG1	Gugub	Sorghum	Hut with roasting	<0.05	290
SVG2	Gugub	Maize	Hut with roasting	0.11	340
SVG3	Gugub	Sorghum	Hut with roasting	<0.05	120
SVG4	Gugub	Maize	Hut with roasting	<0.05	<10
SVG5	Gugub	Sorghum	Reference hut without roasting	0.12	<10
SVG6	Gugub	Maize	Reference hut without roasting	<0.05	<10
SVG7	Taga	Sorghum	Reference hut without roasting	<0.05	<10
SVG8	Taga	Maize	Reference hut without roasting	<0.05	<10

Illustration 43 - Analysis of the sorghum and maize samples.

Two conclusions can be drawn from these results:

- The Hg content of the analysed vegetables is very low both in the reference hut and the hut with roasting.

- Significant quantities of mercury are present in dust deposited on the vegetables hanging from the roofs of huts were roasting is performed (except SVG4). This mercury is eliminated through simple washing with water. This reveals another potential impact of the roasting operation (in addition to the contamination of air during the operation).

These results on sorghum and maize should be controlled in a further step as they apparently will contribute to an evaluation of the daily mercury intake of the local population.

Illustration 44 - Example of sorghum and maize hanging from the roof of a hut

6.7. FISH

At the four fish-sampling spots, catches were made by local fishermen, using nets. Fifteen different species were collected, with a total of 108 individuals (Illustration 22). The 15 fish species collected are shown in Appendix 5. Small dorsal-muscle samples were taken and kept in formalin to be analysed at the University of Bordeaux-CNRS LEESA Laboratory in France.

The main biogeochemical processes linked to mercury input from artisanal gold-mining sites within freshwater systems are summarised in Appendix 5.

Analysis of the results relating to the level of mercury contamination in fish must necessarily bear in mind the constraints imposed by the sampling conditions, and the absence of any direct relationship with the gold-mining site and village of Gugub. Nevertheless, they will show the current state of mercury contamination in the biological component of the hydro systems in this region of Sudan, especially around the dam, which lies downstream from several gold mining sites.

In many countries, fish constitutes a substantial proportion of the protein ration for people living along rivers, lakes and estuaries, In addition to the direct professional exposure of gold miners and their families, fish consumption can thus represent a major source of exposure to MMHg.

6.7.1. Global biometric characteristics and fish mercury contamination levels

Mean biometric data – total body weight (g, wet weight) and standard length (cm) – and mercury concentrations measured in the dorsal skeletal muscle are shown in Illustration 46, for the four sampling spots (1 to 4) and the different species.

As the fish samples were stored in a 10% methanal solution, the Hg analyses carried out on fish muscle are only given in dry weight because the presence of methanal can affect the basic wet weight. However, for fish muscle, a factor of five can be used to convert dry weight into wet weight.

Only five species were common to 2 or 3 sampling spots (Illustration 45), notably between the reservoir (sampling spots: 1, 2, 3) and the water hole north of Gugub (sampling spot 4):

Genus	Species	Sampling spot	Fish number
Clarias	*gariepinus*	1	5
		2	4
		4	1
Oreochromis	*niloticus*	3	5
		4	15
Sarotherodon	*galilaeus*	1	6
		2	5
Schilbe	*intermedius*	1	5
		3	4
Synondontis	*schall*	2	6
		3	6

Illustration 45 - Fish species common between the four sampling spots.

In biometric terms, the fish were small in size, the mean standard length of each species being usually <20 cm. Considerable differences emerged between batches of fish of the same species, but taken from different sampling spots, probably due to differences in age and/or nutritional intake, depending on the sites. For example, for the species *Clarias gariepinus*, marked differences appeared between the body weights from the Roseires reservoir: 17.8±10.6 g (ww) at sampling spot 1; 555.5±46.5 g (ww) at sampling spot 2.

Globally, mercury contamination levels in fish are low to very low. The general mean, from the 108 fish collected, is 0.246±0.048 µg g^{-1}, on a dry weight basis. It must be remembered that concentrations expressed on a wet weight basis, the criterion traditionally used to define safety levels, are about five times lower (wet weight over dry weight = 5). Thus the safety standard defined by the WHO is 0.5 Hg µg g^{-1} on a wet weight basis or 2.5 Hg µg g^{-1} on a dry weight basis (WHO, 1990). The extreme mean values range from 0.056±0.006 µg g^{-1} (dw) for the species *Labeo niloticus* (n = 5) to 0.708±0.052 µg g^{-1} (dw) for the species *Lates niloticus* (n = 6), from sampling spot 1 (Roseires reservoir).

Family	Genus	Species	Food regime	Sampling spot	Standard length (cm)	Body weight (g, fw)	Hg concentration (µg.g-1 dw)	N
Clariiidae	*Clarias*	*gariepinus*	Benthivorous	1	19.7 ± 0.7	76.8 ± 10.6	0.085 ± 0.011	5
Cyprinidae	*Labeo*	*niloticus*	Benthivous	1	15.6 ± 0.4	61.6 ± 4.3	0.056 ± 0.006	5
Schilbeidae	*Schilbe*	*intermedius*	Carnivorous	1	15.6 ± 1.1	47.2 ± 10.1	0.405 ± 0.069	5
Alestiidae	*Hydrocinus*	*forskalii*	Carnivorous	1	21.3 ± 1.5	116.4 ± 21.4	0.694 ± 0.076	5
Centropomidae	*Lates*	*niloticus*	Carnivorous	1	14.1 ± 0.7	55.7 ± 8.7	0.708 ± 0.052	6
Cichlidae	*Sarotherodon*	*galilaeus*	Herbivorous	1	9.0 ± 0.1	24.0 ± 0.9	0.113 ± 0.012	6
Alestiidae	*Brycinus*	*nurse*	Omnivorous	1	13.3 ± 0.2	51.2 ± 1.6	0.107 ± 0.013	5
Clariiidae	*Clarias*	*gariepinus*	Benthivorous	2	39.1 ± 1.7	555.5 ± 46.5	0.098 ± 0.029	4
Cichlidae	*Sarotherodon*	*galilaeus*	Herbivorous	2	16.9 ± 0.6	163.6 ± 12.5	0.105 ± 0.020	5
Mochokidae	*Synondontis*	*schall*	Omnivorous	2	9.6 ± 0.6	20.0 ± 3.7	0.285 ± 0.086	6
Schilbeidae	*Schilbe*	*intermedius*	Carnivorous	3	23.4 ± 0.7	133.5 ± 3.6	0.539 ± 0.085	4
Mormyridae	*Mormyrus*	*niloticus*	Carnivorous	3	24.0 ± 1.0	122.0 ± 16.0	0.098 ± 0.002	2
Cichlidae	*Oreochromis*	*niloticus*	Herbivorous	3	20.3 ± 0.5	266.4 ± 20.4	0.080 ± 0.010	5
Mormyridae	*Marcusenius*	*senegalensis*	Carnivorous	3	21.0 ± 1.0	105.0 ± 7.0	0.103 ± 0.023	2
Mormyridae	*Hyperopisus*	*bebe*	Omnivorous	3	27.5 ± 0.5	189.0 ± 5.0	0.092 ± 0.015	2
Mochokidae	*Synondontis*	*schall*	Omnivorous	3	14.3 ± 0.6	66.0 ± 6.7	0.614 ± 0.149	6
Clariiidae	*Clarias*	*gariepinus*	Benthivorous	4	22.0	68.5	0.243	1
Cyprinidae	*Labeo*	*horie*	Benthivorous	4	9.7 ± 0.7	19.3 ± 3.8	0.194 ± 0.043	14
Cichlidae	*Oreochromis*	*niloticus*	Herbivorous	4	7.3 ± 0.6	16.4 ± 3.4	0.057 ± 0.003	15
Bagridae	*Auchenoglanis*	*occidentalis*	omnivorous	4	22.0 ± 0.1	133.3 ± 64.8	0.150 ± 0.093	2
x	x	x	x	4	11.8 ± 1.5	26.5 ± 7.2	0.336 ± 0.115	4

Illustration 46 - Mean biometric data for fish species collected in the four sampling spots (standard length and body weight, mercury concentrations in the dorsal skeletal muscle and food regime spots (data are means ± standard error – N: number of fish).

6.7.2. Mercury contamination levels according to the fish trophic level and to sampling site

In agreement with the large amount of data available in the literature (for example, Durrieu et al., 2004; Roulet and Maury-Brachet, 2001; Veiga et al., 1999; Wiener et al., 2002), mercury concentrations measured in fish muscle vary according to the food regime of the species and its position along the trophic networks.

Data from sampling spot 1 on the Roseires reservoir (Illustration 47) reveal marked differences between fish species and food regimes. The average concentration for the three carnivorous species (*Schilbe intermedius, Hydrocinus forskalii, Labeo niloticus*) is 0.60 µg g^{-1} (dw). This is about 8 and 5 times higher than those determined for the benthivorous and herbivorous species, respectively. However, these values are clearly below the safety level (2.5 µg g^{-1}, dw).

The relationships between fish body weights and Hg concentrations in the muscle[6] show marked differences between the species collected: for five species, bioaccumulation levels are independent of fish weight. However, for the two carnivorous species - *Lates niloticus* and *Schilbe intermedius* - negative and positive correlations were observed.

Numerous field studies in European countries and in North America have shown a significant positive correlation between Hg concentrations in fish muscle and biometric criteria (body weight or standard length), indicating an increase in bioaccumulation as a function of the age of the fish. Recent studies in Amazonia (Brazil and French Guiana) have shown several types of relationships (no correlation, positive or negative correlations), as a function of fish species, food regimes and also developmental stages (alevins/adults) (Roulet et al., 1999; Frery et al., 2001; Durrieu et al., 2004).

Data from spot 3 on the Roseires reservoir, where six fish species were collected (Illustration 48), show marked differences between the three carnivorous species and also between the two omnivorous species. Several hypotheses can be put forward to explain these results: differences between their ecological niches (for example, for the two omnivorous species, *H. bebe* is described as a demersal species living in the deep layers of the water column; *S. schall* is a benthopelagic species confined to the sediment/water interface); changes in food regimes followed the impact on the foodweb when the reservoir flooded.

No carnivorous species were collected at sampling spots 2 and 4. Minor Hg concentrations were measured in the benthivorous, omnivorous and herbivorous species (Illustration 46). For example, the mean Hg concentration in *Oreochromis niloticus* (N = 15), an herbivorous species, was 0.057±0.003 µg g^{-1} (dw). No significant correlation was observed between body weight and mercury levels in the muscle (Illustration 49).

[6] These relationships were established from a small number of samples. For this reason, their representativeness is limited.

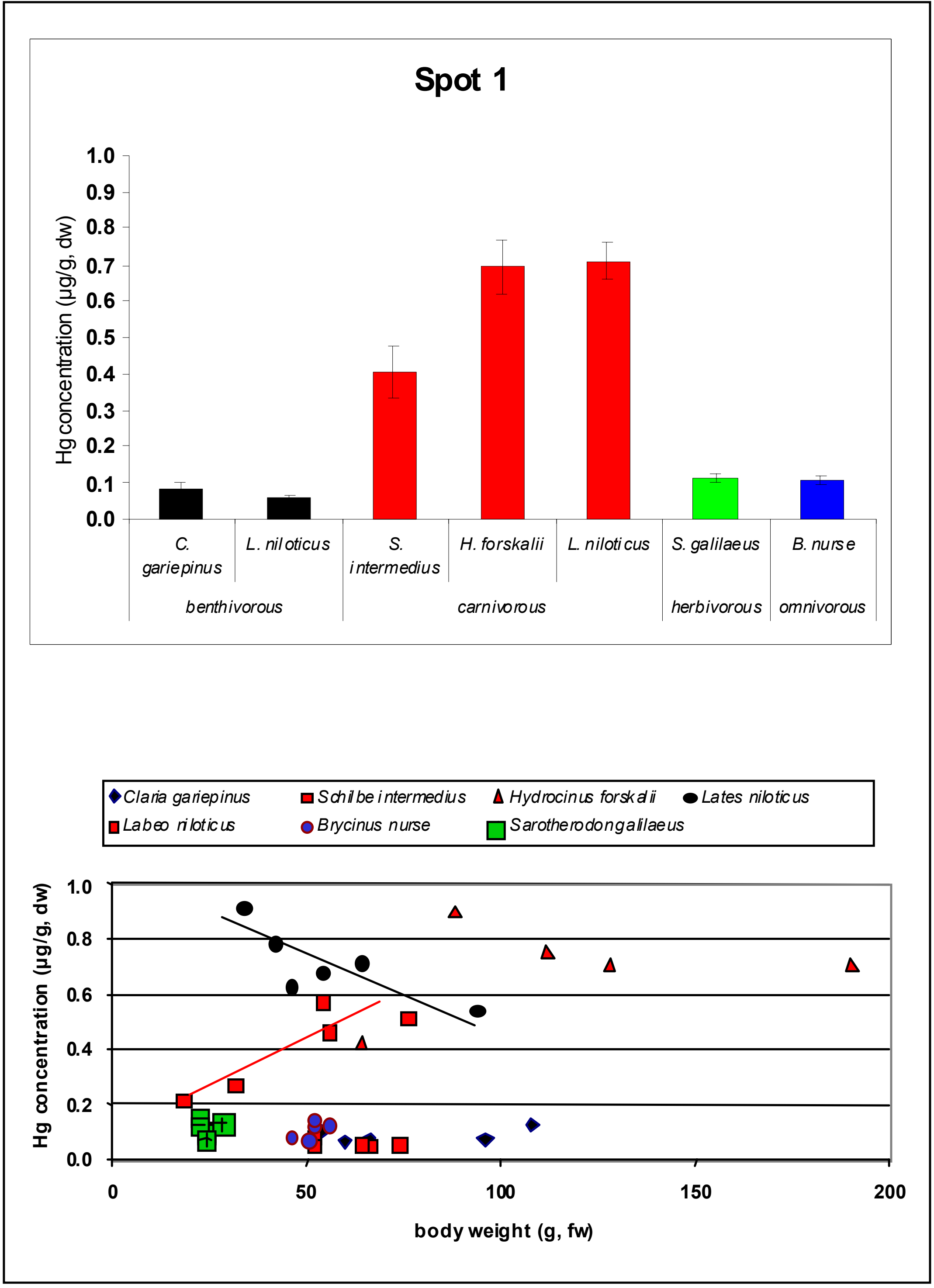


Illustration 47 - Mercury concentrations in the muscle of the seven fish species collected from sampling spot 1 on the Roseires reservoir – relationships between fish body weight and mercury concentration in the skeletal muscle.

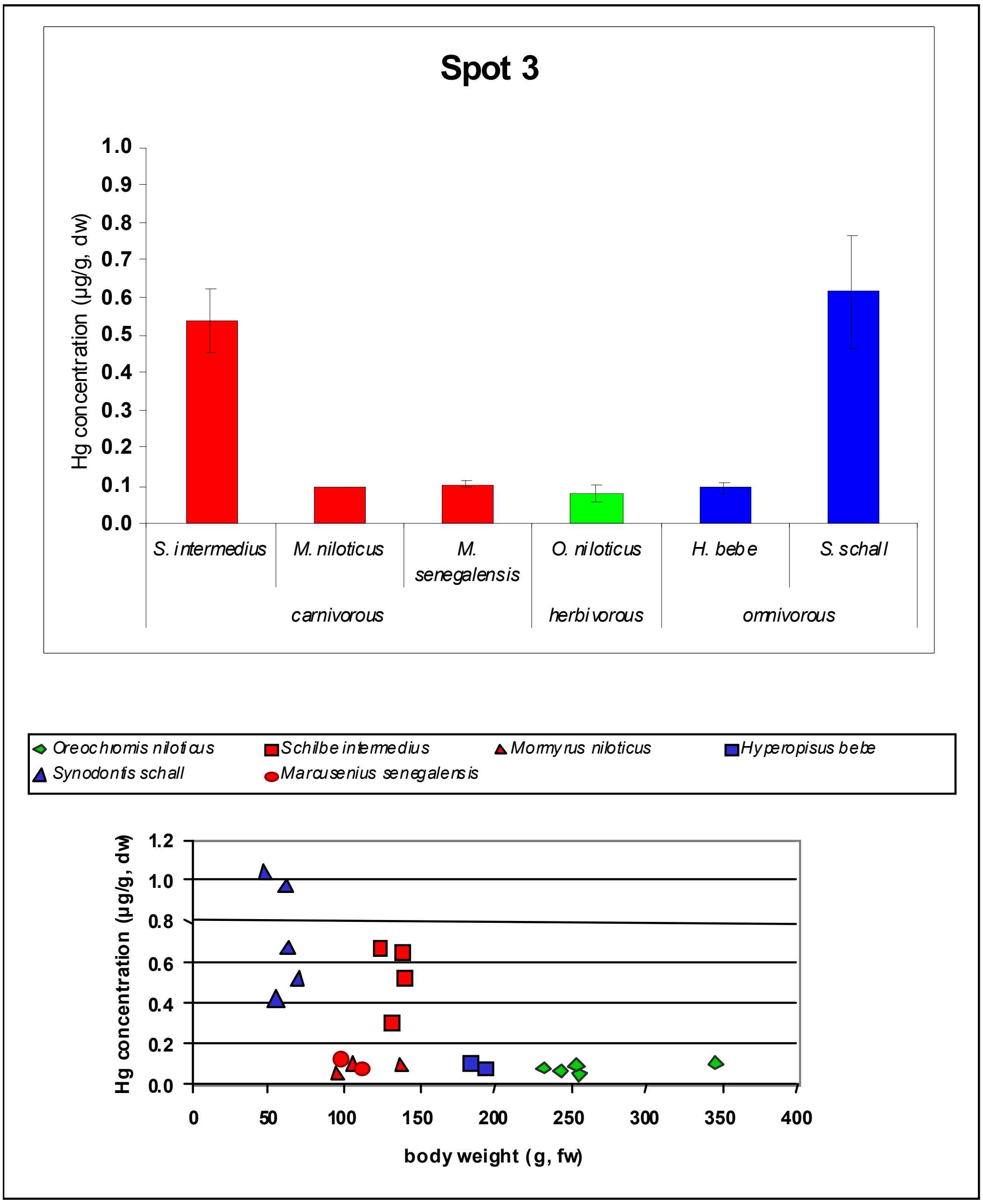


Illustration 48 - Mercury concentrations in the muscle of the seven fish species collected from sampling spot 3 on the Roseires reservoir – relationships between fish body weight and mercury concentration in the skeletal muscle

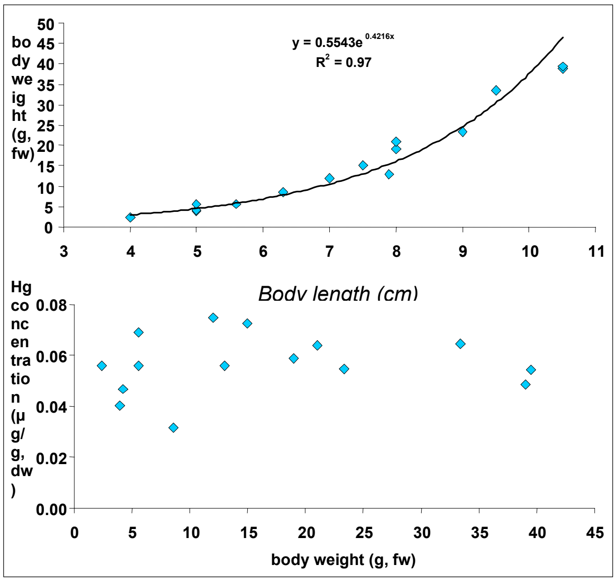


Illustration 49 - Relationships between fish body weight and standard length and between fish body weight and mercury concentration in muscle of the herbivorous species Oreochromis niloticus *(15 individuals) collected from sampling spot 4.*

6.7.3. Conclusions

There is a poor representativeness of mercury contamination levels in fish species in relation to artisanal gold mining in Sudan, probably because of the poor sampling conditions. The Roseires reservoir is 40 years old. Based on comparisons with studies undertaken in Canada, the filling of impoundment lakes no longer affects mercury concentrations after thirty years or so, meaning that the lake is too old to note an increase in mercury concentrations in the fish meat in relation to filling; furthermore, it does not seem judicious to compare Africa with Canada. One probable explanation is that a desert in Sudan became submerged, and that there was very little organic matter and thus few methylation sites. The levels of contamination in fish-muscle samples (15 species - 108 individuals) are very low and there is no fish above the WHO safety limit of 2.5 Hg µg g-1, on a dry weight basis. The global mean Hg concentration was 0.246±0.048 µg g-1 and 0.49±0.10 µg g-1 for the carnivorous species.

It is very difficult to specify a bioindicator on the basis of the samples collected during the Sudan mission. The data are insufficient: only a fraction of the fish caught per site, and a single sample for certain species. The fish populations of the Sudanese rivers are not sufficiently well known at this stage to be able to judge whether the captured species are representative of their environment or not. The data from rivers directly affected by gold-mining sites using amalgamation procedures must be considered insufficient to produce conclusions relating to fish advisory, or to health-related matters for this area of Sudan.

7. Evaluation of exposure to Hg

The ~300 artisanal gold miner families and the 10-15 local gold-merchant shops in Gugub and Khor Gidad constitute the same broad mercury hotspots. The main targets identified are local people. Potential risks to the ecosystem were considered to be minor.

7.1. VILLAGES

Information on mining practices and field study proved that the main risk of exposure to environmental mercury occurs in the villages, as mercury is mostly manipulated at home or around the gold-merchant shops by artisanal miners who take no specific precautions. This risk is increasing because the exposed population is mostly composed of women and their young children working hard on the mining sites. The risk is also present in the huts or in the yard of a “family unit”.

The probability of occurrence of exposure to mercury is summarised in Illustration 50.

Inhalation

Here, inhalation concerns only volatilised Hg°. The monitoring of air quality showed that Hg concentrations may reach relatively high concentrations. However, exposure of the artisanal miners was relatively short compared to the exposure limits for professional workers exposed to mercury (e.g. 25 µg m^{-3} average air concentration for an 8 hour shift, WHO, 1994). We measured that people are only exposed to elevated mercury concentrations for about 10 to 15 mn during the amalgam roasting. Roasting takes place outside or inside the hut depending on the families. When roasting is done indoors, the same fireplace is used for cooking. Most of these demonstrations were done by men, but in the presence of women and children. For this reason, we should also consider the possible exposure of women and children and use air quality standards for non professional exposure.

	Description	Probability of occurrence	Comments
SOURCES	- Accidental Hg spill during deals or amalgamation - Amalgam roasting - Disposal of contaminated tailings	*** *** **	
TRANSFER & PATHWAYS	- Hut dust contamination - Hg vapour dissemination contaminating the hut and its close environment - Soil contamination in the vicinity of contaminated huts - Sediment contamination by panning of tailings in pools	*** *** ? *	- Contamination of the soil of the mosque and other "reference" spots - Occasional
HUMAN TARGETS	- Hg inhalation during roasting - Domestic dust and soil ingestion (mostly children) - Fish consumption - Vegetable consumption - Contaminated poultry consumption[1] - *Drinking water*[1]	** *** * * ? ?	- Main situation of Hg inhalation - Needs further control - Needs further control - Possible contamination of poultry ? - Needs further control

Illustration 50 - Probability of occurrence to Hg exposure ([1] not considered in that study).

Ingestion

In the described system, oral exposure may occur in different situations like soil and dust ingestion or food consumption.

We demonstrated that huts of artisanal miners are contaminated due the procedure of amalgam roasting in the hut. Thus walls, suspended sorghum and maize and domestic dust are contaminated in the hut of artisanal miners. Metallic mercury may progressively accumulate in the houses during the mining season. We showed that domestic dust may reach high concentrations (up to 840,000 ng g^{-1}). We estimate that it constitutes one of the main risks of exposure for the population, and particularly for children.

The soil of the school playground of the Gugub village is not contaminated. Soils in and around the shops or soils of amalgamation areas around huts of artisanal miners show the same high levels of contamination than the dust inside the huts (mean 2,480-40,230 ng g^{-1}). Such concentrations are relatively high compared to threshold values for soils in residential areas (7,000 to 10,000 ng g^{-1} in Europe) (Illustration 51). However, the higher values are related to specific restricted areas (shops, amalgamation areas of several square metres in size). Except these hotspots, Hg contents of the yard soils in both villages are on average lower (mean 763 – 2,116 ng g^{-1}) and clearly below the threshold values mentioned before.

The amount of soil and dust that is ingested has been discussed extensively in the literature (Simon, 1998; Calabrese, 1989, Calabrese *et al.*, 1991), but there is no existing guideline value for mercury for soil and dust ingestion. Geophagic activity has not been described by the sociological study. Data collected during this work were not sufficient to appreciate the real quantity of inadvertent ingestion of dust and soil by persons. Dust ingestion (soil + domestic dust) could be relatively important for children (especially under the living conditions of local people), and this may cause a potential risk of contamination for the artisanal miners and their families.

A possible contamination of poultry may exist in relation with contaminated soils and domestic dust. This point was not checked because the field survey took place during the avian flu crisis of 2003-04, when it was forbidden to sample and import poultry meat in Europe.

The other risk of exposure is related to the consumption of fish and vegetables (sorghum and maize). There is a poor representativeness of mercury contamination levels in fish species in relation to artisanal gold mining owing to the poor sampling conditions. The levels of contamination in fish-muscle samples (15 species - 108 individuals) is very low and no fish exceeded the WHO safety limit of 2.5 Hg µg g^{-1}, on a dry weight basis; the global mean Hg concentration was 0.246±0.048 µg g^{-1} and 0.49±0.10 µg g^{-1} for the carnivorous species. Being located ~50 km away from the Blue Nile, the community of Gugub and its surroundings has no regular access to fresh fish supplies. However, dried fish is available in the Gugub market. The occasional consumption of fish in that area, (only 2% of the people report eating fish occasionally) does not seem to constitute a major risk. However, the data from rivers directly affected by gold-mining using amalgamation procedures must be considered insufficient to draw conclusions relating to fish consumption, or to health related matters for this area of Sudan.

Sorghum and maize porridge constitute the main meal of the communities. In the Gugub and Khor Gidad, women cultivate maize and sorghum along stream terraces, or in small private gardens close to the huts and Hg-processing spots. The average contents in garden ranging between 130 and 280 ng g^{-1} are close to the background level, and below the UK and Canadian standards of permissible Hg concentrations in agricultural soil ranging from 1,000 to 8,000 ng g-1. The Hg content of the analysed sorghum and maize is very low and does not present a risk, but significant quantities of mercury are present in the dusts deposited on the vegetables hanging from the roofs of huts were roasting is performed. This mercury is eliminated by a simple washing with water. These results on sorghum and maize should be controlled in a further step as apparently they may contribute to the evaluation of the daily intake of mercury for the local population.

7.2. WADIS AND KHORS

There is no major flowing river close to the mining and processing areas, only seasonal drainage. Miners pan alluvial gold on banks and terraces when local stream are flowing during the rainy season between July and December, but in those sites miners do not use mercury and recover only visible gold. It appears that in Gugub and Khor Gidad villages, the mercury pollution of stream sediments could be mainly controlled by the surface run-off from gold amalgamation and roasting processing sites located in the villages. We assume that Fe-rich laterite and seasonal run-off probably act as natural barriers against this type of Hg dispersion in the sediments.

In Gugub and Khor Gidad, most of the sediment samples show concentrations <400 ng g^{-1}. In the village of Khor Gidad, Hg contents are mainly <200 ng g^{-1} without apparent contamination downstream. In the village of Gugub, the highest values (1,066 to 1,649 ng g^{-1}) are located along Khor Alyas where during the rainy season part of the tailings and residues are sometimes panned in pools. This practice appears as the only one presenting a risk for the local streams.

Downstream, the Hg concentrations in sediments of the main collector, Wadi Maganza, are relatively low (42 to 148 ng g^{-1}) and do not show important levels of contamination compared to the usual guideline values for sediment management in Europe or the North America.

It is not possible to compare the results obtained on dry samples from the villages of Gugub and Khor Gidad, where precise sampling of one layer or a particular place in the stream was possible, with samples taken somewhere else in flowing rivers. Analysis of the results relating to the level of mercury contamination in the sediment must necessarily bear in mind the constraints imposed by the sampling conditions, the absence of any flowing water observed during the mission, the limited number of samples taken in Wadi Maganza, and the fact that intensive use of mercury in the area is quite recent.

The sampling conditions, focused on dry samples rich in organic matter, may for example partially explain some of the high values encountered close to the villages. Anthropogenic Hg contamination of sediments exists in the villages where amalgamation and roasting take place, but it seems restricted to a narrow zone of a few hundred metres wide, and, today, without apparent contamination downstream through Wadi Maganza. These elements show that the stream appears as a preserved natural ecosystem.

		Mean values	Max.	(unit)	Guideline values
Fish	Roseires dam	0.25	0.7	µg g^{-1} (dw)	2.5 WHO safety limits
	Roseires - Carn.	0.6	2.5		
	Others	0.15	0.3		
Sediments	Villages	196-308	1649	ng/g	700 PEL (US)
	Roseires dam	250	386		200 (LEL Canada)
	Wadi Maganza	75	148		2000 (SEL Canada)
Vegetables	Sorghum & corn	< 0.05	0.12	µg g^{-1} (dw)	background <0.1
	Cleaning water	250	340	ng (for 50ml)	
Air	Sqeezing	500		ng m^{-3}	200 MRL inhalation, WHO, 2000
	Amalgam roast.	90,000-100,000			1,000 (NOAEL, WHO, 2000)
	Fire lighting	200-300			25,000 / 8h (WHO prof. exposure)
Soil & tailings	Villages	2,480-40,230	1,000,000	ng g^{-1}	27 ng/g PNEC (INERIS, 2003)
	Ref. background	100	150		
Domestic dust	Ref. village	180		ng g^{-1}	none
	Miners village	1,236-103,000	840,000		7,000 ng/kg/day MRL , WHO, 2000

Illustration 51 - Synthesis of the results and published guideline values. (PEL : Probable Effect Level; LEL : Low Effect Level; SEL : Strong Effect Level; MRL : Minimum Risk Level; NOAEL : No Effect Level; PNEC : Probable Non Effect Concentration)

8. Conclusions & recommendations

The operation was carried out in collaboration between French teams (BRGM, Universities of Montpellier and Bordeaux) and Sudanese teams (Geological Research Authority of Sudan and University of Nileen). The sampling campaign and health survey took place from March 29th to April 18th, 2004 during the hot dry summer before the rainy season and the main alluvial mining season. The aim of this study was to collect environmental and health data in the Gugub and Khor Gidad villages of the Bau district in the Ingessana Hills (Blue Nile State of Sudan), to assess the level of mercury exposure of local communities and the potential impact on the environment. Another small village, Taga was added as a reference village (i.e. a village without a mining history). There was no major flowing river close to the mining and processing areas, only seasonal drainage. No flowing water was observed during the mission, although there were small pools along main wadis. There was no panning activity.

Mining of gold-bearing quartz veins was the only type we observed during the field mission.

8.1. MAIN OUTCOMES OF THE ENVIRONMENTAL SURVEY

Use of mercury

Use of mercury in the area is quite recent and depends on the type of mining activities.

Artisanal gold mining activities in the Ingessana Hills started in 1996. Intensive use of mercury in the area is quite recent (about 3 years or less) and is mainly developed in Gugub, where gold was first discovered, and in Khor Gidad after the gold rush of September 2003. During our mission, those two sites were the only ones in activity. At the present time, the village of Khor Gidad is an extraction and processing site and the village of Gugub is a processing site only. The other sites mentioned in the sociological reports (i.e. Turda, Khor Neiwi) are alluvial types, without mercury use and presently abandoned.

Miners pan alluvial and eluvial gold when local stream are flowing during the rainy season between July and December. In those sites miners do not use mercury and recover only visible gold during the rainy season. Results of Hg Analyses carried out for this study confirm this assumption: soils, tailings and sediments sampled around alluvial panning areas are not contaminated by Hg.

During the dry season, due to a shortage of water on pit sites, only primary gold associated with quartz veins is mined. The procedures used by local people are representative of very poor people using simple and traditional practices. Mercury is used only to recover gold from this primary ore. Most of these activities were performed by women (13-35 years old), including the hard tasks of digging and excavation. Men are only involved in mining at greater depths and in roasting. There is no use of Hg on the mining site, the selected ore being transported to the village for crushing, manually milling and panning in the yard of “family units”.

Gold production and mercury consumption

Gold production estimates based on two independent sources (worker’s production and dealers) gave similar results: the quantity of gold produced from quartz veins in the two studied villages is 75-300 g Au/day and 22.5-90 kg Au/year. Workers and dealers probably underestimated their production and actual values may be higher.

We demonstrated that to produce such quantities (100-300 g Au/day) from the Gugub sites, 800 to 1000 workers must be involved and gold grades should be 30 to 72 g t^{-1} respectively. According to available data and observations made (average gold grades measured by GRAS of less than 5 g t^{-1} and 300 families living on the sites), the works in Gugub can not produce the quantity of gold mentioned before from quartz-vein mining alone. A large part of the gold sold during the dry season (probably 50%) probably comes from alluvial production and also from gold reserves made by workers during the rainy season. According to our field observations and the estimates, the use of mercury in the Gugub district is between 250 and 500 g Hg per household of artisanal miners.

Taking into account these data, the ratio of Hg lost/Au produced is probably over 3 in the Gugub area.

Contamination due to amalgamation practices

According to analysis of the process, the most probable sources of soil contamination are related to solid deposition of mercury during the amalgamation process, to atmospheric deposition of mercury during the roasting, and to dissemination of household dust around artisanal miner huts.

Final panning followed by amalgamation are performed in one daily sequence at home or close to the shops selling mercury. In both cases, there is no specific place for amalgamation. The miners collect the amalgam by hand, taking no precautions.

Soils in the yards are contaminated by Hg. The average geochemical Hg contents in the villages of Gugub and Khor Gidad are ten times higher than the local background (100 to 150 ng g^{-1}). The contamination is punctual with probable nugget effects. Higher values in the two villages (up to 10^6 ng g^{-1} in Khor Gidad and up to 27,626 ng g^{-1} in Gugub) are related to amalgamation zones where Hg droplets can be seen after panning. These zones, showing values several times higher than other places where values are close to local background, are major hotspots.

The school yard in Gugub shows background Hg contents (106 ng g^{-1}).

Contamination due to roasting of amalgam

The gold amalgam is roasted in the village in mobile bonfires, outside near the dealer's shop where they buy mercury; in the yard of "family units", or inside the huts. It was rather difficult to identify what was the main place of roasting. In Khor Gidad, roasting outside seems to be the norm, whereas in Gugub the proportion is about 50-50. Roasting is mostly done by men, who take no precautions.

Domestic dust in some huts and yards of artisanal miners also show significant contamination (500 - 2,760 ng g^{-1} in Gugub and 123 - 840,000 ng g^{-1} in Khor Gidad). It is clear that indoor amalgam roasting may significantly contaminate the dust of the huts but there are no major differences between Hg contents in soils compared to the general Hg content of dusts in the villages. Also, there is no significant difference depending on the dust location (hut with or without roasting). It was impossible, at this stage of investigation, to appreciate the ratio between soil contamination by amalgamation and by roasting. The information supplied by the inhabitants can be vague, but our results show at least that the contamination is rather general and homogeneous on the scale of both a household and that of the village as a whole.

Monitoring of the air quality inside and outside huts showed that Hg concentrations can reach relatively high concentrations (≥25,000 ng m^{-3}). However, in the worst cases the exposure of the artisanal miners, mainly during roasting or around 10 mn per day, was relatively short compared to the exposure limits for professional workers. Amalgam roasting seems to be an occasional procedure occurring on a daily or weekly basis.

However as some roasting is done in huts, we should also consider the possible exposure of children. The roasting of amalgam usually generates two Hg peaks >24,000 ng m^{-3}. The first peak appears when Hg is evaporating from the amalgam, the second one, a few minutes later, is probably due to a late recondensation of mercury aerosols emitted during roasting. This condensation phase indicates that a large part of mercury emitted in the hut remains inside and therefore could accumulate in dust on the floor, on walls, and on vegetables hanging from the roof of the hut. The second point is that this condensation phase could concern the entire hut, unlike the period of roasting (local evaporation near the fire). All people present in the hut at this moment could therefore inhale this mercury vapour. The condensation effect is lower in huts allowing good smoke evacuation due to openings at the junction of walls and roof.

For outside roasting, the duration of high mercury concentrations is shorter than in the hut (around 100 s compared to 500 s in a hut) and the second peak of probable condensation of mercury vapour observed in the hut is absent.

Remobilisation of Hg in stream sediments

The remobilisation of Hg from processing areas to local streams seems very low. Hg contents in sediments of wadis and khors flowing from the villages of Gugub and Khor Gidad are similar (median <200 ng g^{-1}) with higher contents near amalgamation zones (villages). The Hg contents decreased a few hundred metres downstream from the mining villages. Hg concentrations in sediments of the main collector Wadi Maganza are also relatively low and do not show high levels of contamination when compared to the usual guideline values for sediment management in Europe or in North America. It is not possible to compare the results obtained on dry samples from the villages of Gugub and Khor Gidad with samples taken somewhere else in flowing rivers. The sampling conditions, which focused on dry samples with organic matter, explain certainly partially the high values encountered. Hg contamination of sediments exists in the villages where amalgamation and roasting occur, but it seems restricted to a narrow zone of few hundreds of metres around such processing spots and, at the present time, without apparent contamination downstream through Wadi Maganza.

Contamination of tailings and effect on streams

Grinding, amalgamation and roasting of ore generate heaps of mixed tailings, residues, ash or waste, sometimes several cubic metres in size, and often thrown on the ground near the zones of operation, in or around dwelling enclosures, or even in gardens. Hg analyses carried out on these tailings show a heterogeneous contamination depending on their composition, which locally can be high to very high (62,300 and 72,500 ng g^{-1} in Khor Gidad). Their number and location in gardens or within “family units” is a problem to be taken into account during future environmental management operations in the area.

Workers indicated that during the rainy season part of the tailings and residues are panned in pools located in the Khor Alyas*,* south of Gugub. The highest Hg contents in sediment (1,066 to 1,649 ng g^{-1}) are located along this stream bed where aquatic life is unknown, but where a water well is located supplying the village with drinking water. Control analyses on water well must be carried out in priority.

Main hotspots

The ~300 artisanal gold miner families and the 10-15 local gold-merchant shops in Gugub and Khor Gidad constitute the same broad mercury hotspots. Potential risks to the ecosystem were considered to be minor. The main targets identified are local people practising gold concentration processes at home. Shops and their surroundings represent further particular hotspots: the strongest Hg contents come from soil and dust on the ground of trade shops (values ranging from 20,000 to 1,000,000 ng g^{-1}).

We identified 4 sources of lost of mercury in the environment:

- Wrong manipulation of mercury in the shop or at home;
- Loss of Hg on the ground or in tailings during the amalgamation phase;
- Evaporation during the roasting phase;
- Occasional panning of tailings in the pools.

Consumption of fish and vegetables

The other, minor, risk of exposure is related to the consumption of fish and vegetables (sorghum and maize). There is a poor representativeness of mercury contamination levels in fish species in relation to artisanal gold mining owing to unsatisfactory sampling conditions. The levels of contamination in fish-muscle samples (15 species - 108 individuals) is very low and no fish was above the WHO safety limit of 2.5 Hg µg g^{-1}, on a dry weight basis – the global mean Hg concentration was 0.246±0.048 µg g^{-1} and 0.49±0.10 µg g^{-1} for carnivorous species. Compared with Zimbabwe, for fish of a similar size, the mean Hg concentrations were about ten times lower. Analysis of the results relating to the level of mercury contamination in fish must necessarily consider the constraints imposed by sampling conditions and the absence of any direct relationship with the gold-mining site and village of Gugub. The occasional consumption of fish there, (only 2% of the people report eating fish occasionally) does not seem to constitute a major risk. The data from rivers directly affected by gold-mining sites using amalgamation procedures must be considered insufficient to draw conclusions relating to fish advisory, or health related matters for this area of Sudan

Sorghum and maize are the main consumed vegetables during the dry season. The average Hg contents in garden soil (cultivation of sorghum and maize) around “family units” are 130 and 280 ng g^{-1} in Khor Gidad and Gugub, respectively. These values are close to the background level, and below UK and Canadian standards of permissible Hg concentrations in agricultural soil, ranging from 1,000 to 8,000 ng g^{-1}. This indicates low mercury remobilisation, probably due to Fe-rich laterite acting as natural barriers and attenuating the widespread dispersion of Hg.

Hg contents of the analysed sorghum and maize are very low and do not present a risk, but significant quantities of mercury are present in the dust deposited on vegetables hanging from the roofs of huts were roasting is performed. This mercury is eliminated by simply washing with water. These results on sorghum and maize should be controlled in a further step as they may contribute to evaluation of the daily intake of mercury by the local population.

8.2. RECOMMENDATIONS

This study was conducted over a short period and does not allow final conclusions in term of impact assessment. Some aspects would require further specific control.

- In wadis and khor, the sampling of fish and sediments should be extended during the rainy season, especially along Wadi Maganza, to evaluate the real level of mercury contamination in the river system. The first results indicate that the risk of high contamination of fish is low.
- The environmental assessment concerned only the environment of artisanal miners. Contamination of gold shops and their surroundings was proved in both villages studied. We also expect that roasting tends to be incomplete and at least 15-25% of the *“doré”* contains residual mercury. To complete this assessment, particular

attention should be paid to the more exposed parts of the population that is constituted by dealers, merchants and their families.

- Contamination results on sorghum and maize should be controlled in a further step as apparently they will contribute to evaluation of the daily intake of mercury by the local population. The washing of hands and vegetables should be a priority, even if sometimes water is restricted in use.

As the practice of local artisanal miners is quite recent, very traditional and with a limited use of mercury, there is no strong need to propose an major programme for developing alternative technologies on a short-term basis. However, we strongly recommend that some habits in the artisanal mining practices be changed. To effect such changes would require an awareness raising campaign with education of population, and especially women who tend to be heavily involved, concerning the risks they and their children face. The action should focus on the amalgamation and the roasting procedures in order to promote safer working methods.

- The main objective is a change in the location of amalgam roasting. Outside roasting is strongly recommended and exposure to mercury vapour could be avoided through the application of simple technological improvements such as retorts. Roasting the amalgam does not seem to be a private and confidential activity. It is commonly carried out in the street or at the shops. This fact can help to work in collaboration with the local artisanal miners to identify appropriate spots, distant from the village and dedicated to roasting. Such spots should be designed to avoid dispersion of Hg in the environment. Presence of children and pregnant women should be avoided during roasting.
- Authorities need to ensure that all amalgamation is carried out in cemented places and that all tailings from the amalgamation are stored in appropriate cemented storage areas that prevent dispersal of Hg contamination onto adjacent land and into drainage.
- Careful clean-up of contaminated huts is recommended in order to decrease the Hg content of domestic dust.
- Amalgamation areas located in “family units” must be marked and fenced in order to prevent the ingestion of amalgamation residues by children or animals.
- As use of mercury is recent, the most urgent requirement is to prevent any new Hg input into river sediments by stopping, or at least strictly controlling, panning of contaminated tailings in the pools during the rainy season.

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Appendix 1

List of dust samples

SAMPLE	SAMPLING		COORDINATE DD		ALT	AREA	SITE	SPOT	SAMPLE	LOCATION		ACTIVITY
N°	DATE	TIME	LAT N	LONG E	m	NAME		N°	TYPE			ZONE
SDU001	09-APR-04	09:18:36	11.37455	34.01638	789.4	GUGUB	VILLAGE	1	DUST	Family unit	Hut	Roasting
SDU002	09-APR-04	09:51:02	11.37393	34.01635	791.0	GUGUB	VILLAGE	2	DUST	Shop	Shop	
SDU003	09-APR-04	10:15:28	11.37385	34.01615	792.0	GUGUB	VILLAGE	2	DUST	Shop	Yard	
SDU004	09-APR-04	10:24:23	11.37390	34.01621	790.1	GUGUB	VILLAGE	2	DUST	Shop	Hut	Roasting
SDU005	09-APR-04	11:16:40	11.37385	34.01647	792.0	GUGUB	VILLAGE	3	DUST	Family unit	Hut	Roasting
SDU006	09-APR-04	15:13:42	11.37542	34.01535	785.5	GUGUB	VILLAGE	4	DUST	School	Yard	Reference
SDU007	09-APR-04	15:31:50	11.37418	34.01632	790.1	GUGUB	VILLAGE	5	DUST	Mosque	Yard	Reference
SDU008	09-APR-04	17:08:30	11.37411	34.01662	795.4	GUGUB	VILLAGE	7	DUST	Family unit	Hut	Roasting
SDU009	10-APR-04	08:56:47	11.37447	34.01649	792.2	GUGUB	VILLAGE	1	DUST	Family unit	Hut	
SDU010	10-APR-04	09:02:43	11.37391	34.01621	787.4	GUGUB	VILLAGE	2	DUST	Family unit	Hut	
SDU011	10-APR-04	09:34:04	11.37284	34.01787	784.1	GUGUB	VILLAGE	9	DUST	Family unit	Hut	Roasting
SDU012	10-APR-04	10:21:11	11.37093	34.02053	771.3	GUGUB	VILLAGE	10	DUST	Family unit	Hut	Reference
SDU013	10-APR-04	11:46:16	11.36847	34.01578	812.7	GUGUB	VILLAGE	11	DUST	Family unit	Hut	Roasting
SDU014	11-APR-04	14:02:33	11.37190	34.01658	783.8	GUGUB	VILLAGE	27	DUST	Shop	Shop	
SDU015	11-APR-04	14:15:29	11.37195	34.01635	779.5	GUGUB	VILLAGE	27	DUST	Shop	Hut	
SDU029	15-APR-04	11:10:45	11.37428	34.01710	791.8	GUGUB	VILLAGE	64	DUST	Family unit	Hut	
SDU016	11-APR-04	15:47:06	11.41933	34.02030	742.3	KHOR GIDAD	VILLAGE	28	DUST	Shop	Hut	Reference
SDU017	11-APR-04	16:06:04	11.41924	34.02034	735.5	KHOR GIDAD	VILLAGE	28	DUST	Shop	Yard	Roasting
SDU018	11-APR-04	16:26:16	11.41868	34.02063	739.1	KHOR GIDAD	VILLAGE	29	DUST	Dealer Dwelling	Hut	
SDU019	11-APR-04	16:33:08	11.41886	34.02069	736.5	KHOR GIDAD	VILLAGE	29	DUST	Dealer Dwelling	Hut	Roasting
SDU020	11-APR-04	16:56:20	11.41887	34.02088	743.5	KHOR GIDAD	VILLAGE	30	DUST	Shop	Yard	Roasting
SDU021	11-APR-04	17:12:23	11.41741	34.02087	746.3	KHOR GIDAD	VILLAGE	31	DUST	Shop	Hut	
SDU022	11-APR-04	17:21:11	11.41742	34.02084	737.5	KHOR GIDAD	VILLAGE	31	DUST	Shop	Yard	Roasting
SDU023	11-APR-04	17:28:53	11.41746	34.02100	738.7	KHOR GIDAD	VILLAGE	31	DUST	Shop	Shop	Dealing
SDU024	11-APR-04	18:13:04	11.41650	34.02117	736.5	KHOR GIDAD	VILLAGE	32	DUST	Shop	Shop	Dealing
SDU025	11-APR-04	18:16:57	11.41643	34.02124	741.5	KHOR GIDAD	VILLAGE	32	DUST	Shop	Yard	Roasting
SDU026	12-APR-04	10:30:06	11.41713	34.02117	740.1	KHOR GIDAD	VILLAGE	33	DUST	Shop	Hut	
SDU027	12-APR-04	12:21:11	11.41975	34.01910	748.0	KHOR GIDAD	MINING	35	DUST	Miner Dwelling	Hut	
SDU028	14-APR-04	10:50:06	11.41315	34.02100	736.7	KHOR GIDAD	VILLAGE	47	DUST	Miner Dwelling	Hut	
SDU030	15-APR-04	13:21:57	11.38844	34.05503	713.4	TAGA	VILLAGE	66	DUST	Family unit	Hut	Reference

SAMPLE N°	Description
SDU001	fine dust in the roasting hut coming from ground and roof (living site)
SDU002	fine wet dust on the ground of the shop; monitoring 2 in front of the street
SDU003	fine dust in the living yard
SDU004	fine dust in the roasting hut coming from ground and roof (living site) poorly ventilated
SDU005	fine dust in the roasting hut coming from ground and roof (living site) Monitoring 1
SDU006	reddish dust from the ground; school could be considered as the reference point without Hg use in the village
SDU007	reddish dust from the ground front of the mosque; mosque could be considered as the reference point without Hg use in the village
SDU008	brown to grey dust in a hut with frequent roasting
SDU009	fine dust on the ground , sleeping hut without roasting
SDU010	fine dust on the ground , sleeping hut without roasting
SDU011	fine dust on the ground
SDU012	fine dust in the living hut (Ingessana Tribe- IT)
SDU013	fine dust
SDU014	fine greyish dust on the ground
SDU015	fine greyish dust on the ground (no roasting hut)
SDU016	fine dust from the ground (no roasting)
SDU017	fine dust around usual roasting area
SDU018	fine dust in the living hut (no roasting)
SDU019	fine dust in the living hut (roasting)
SDU020	reddish fine-grained soils, ash on the top
SDU021	fine dust (no roasting)
SDU022	fine dust (ash) around roasting area
SDU023	fine dust on the ground
SDU024	fine dust
SDU025	fine dust (ash) around roasting area
SDU026	fine dust in the living hut (no roasting)
SDU027	fine dust , quite new Hut (no roasting, no amalgamation
SDU028	fine dust
SDU029	fine dust
SDU030	fine dust in the living hut

Appendix 2

List of the soil samples

SAMPLE	SAMPLING		COORDINATE DD		ALT	AREA	SITE	SPOT	SAMPLE	LOCATION		ACTIVITY
N°	DATE	TIME	LAT N	LONG E	m	NAME		N°	TYPE			ZONE
SSO001	09-APR-04	08:42:01	11.37443	34.01642	789.8	GUGUB	VILLAGE	1	SOIL	Family unit	Yard	Amalgamation
SSO002	09-APR-04	09:10:20	11.37460	34.01641	788.4	GUGUB	VILLAGE	1	SOIL	Family unit	Yard	
SSO003	09-APR-04	09:25:51	11.37450	34.01642	789.6	GUGUB	VILLAGE	1	SOIL	Family unit	Yard	
SSO004	09-APR-04	09:40:09	11.37434	34.01647	793.7	GUGUB	VILLAGE	1	SOIL	Garden	Garden	
SSO005	09-APR-04	10:07:11	11.37391	34.01625	794.2	GUGUB	VILLAGE	2	SOIL	Shop	Yard	Amalgamation
SSO006	09-APR-04	10:32:38	11.37385	34.01614	794.4	GUGUB	VILLAGE	2	SOIL	Shop	Yard	
SSO007	09-APR-04	11:21:58	11.37375	34.01644	788.6	GUGUB	VILLAGE	3	SOIL	Family unit	Yard	Amalgamation
SSO008	09-APR-04	12:24:30	11.37367	34.01657	792.0	GUGUB	VILLAGE	3	SOIL	Garden	Garden	
SSO009	09-APR-04	15:17:43	11.37560	34.01522	786.7	GUGUB	VILLAGE	4	SOIL	School	Yard	Reference
SSO010	09-APR-04	15:38:03	11.37411	34.01640	791.8	GUGUB	VILLAGE	5	SOIL	Mosque	Yard	Reference
SSO011	09-APR-04	16:49:42	11.37354	34.01679	789.1	GUGUB	VILLAGE	3	SOIL	Garden	Garden	
SSO012	09-APR-04	17:07:12	11.37409	34.01660	796.3	GUGUB	VILLAGE	6	SOIL	Family unit	Yard	Amalgamation
SSO013	09-APR-04	17:24:30	11.37305	34.01716	793.7	GUGUB	VILLAGE	7	SOIL	Family unit	Yard	Amalgamation
SSO014	09-APR-04	17:35:52	11.37270	34.01744	789.8	GUGUB	VILLAGE	7	SOIL	Garden	Garden	
SSO015	09-APR-04	17:40:52	11.37312	34.01769	784.8	GUGUB	VILLAGE	7	SOIL	Garden	Garden	
SSO016	10-APR-04	09:41:41	11.37287	34.01775	786.5	GUGUB	VILLAGE	8	SOIL	Track	Track	Amalgamation
SSO017	10-APR-04	10:16:42	11.37088	34.02045	783.1	GUGUB	VILLAGE	9	SOIL	Family unit	Yard	
SSO018	10-APR-04	11:18:19	11.36851	34.01571	772.3	GUGUB	VILLAGE	10	SOIL	Family unit	Yard	Reference
SSO019	10-APR-04	11:25:26	11.36827	34.01578	812.4	GUGUB	VILLAGE	11	SOIL	Family unit	Yard	Amalgamation
SSO020	10-APR-04	11:38:13	11.36847	34.01578	809.1	GUGUB	VILLAGE	11	SOIL	Family unit	Yard	Amalgamation
SSO021	10-APR-04	11:53:48	11.36849	34.01584	810.8	GUGUB	VILLAGE	11	SOIL	Family unit	Yard	
SSO022	10-APR-04	13:55:45	11.37182	34.01669	811.0	GUGUB	VILLAGE	11	SOIL	Family unit	Garden	
SSO023	11-APR-04	14:07:42	11.37190	34.01652	782.2	GUGUB	VILLAGE	27	SOIL	Shop	Yard	Amalgamation
SSO024	11-APR-04	14:18:18	11.37189	34.01661	792.0	GUGUB	VILLAGE	27	SOIL	Shop	Yard	Amalgamation
SSO025	11-APR-04	15:43:17	11.41923	34.02028	781.4	GUGUB	VILLAGE	27	SOIL	Shop	Yard	Roasting
SSO026	11-APR-04	15:48:59	11.41928	34.02028	739.6	KHOR GIDAD	VILLAGE	28	SOIL	Shop	Yard	Amalgamation
SSO027	11-APR-04	15:53:51	11.41938	34.02038	740.8	KHOR GIDAD	VILLAGE	28	SOIL	Shop	Yard	Amalgamation
SSO028	11-APR-04	15:59:06	11.41925	34.02036	741.5	KHOR GIDAD	VILLAGE	28	SOIL	Shop	Yard	Amalgamation
SSO029	11-APR-04	16:19:05	11.41879	34.02061	739.9	KHOR GIDAD	VILLAGE	28	SOIL	Shop	Yard	Reference
SSO030	11-APR-04	16:36:09	11.41859	34.02059	741.3	KHOR GIDAD	VILLAGE	29	SOIL	Dealer Dwelling	Yard	Amalgamation
SSO031	11-APR-04	16:48:39	11.41882	34.02086	741.1	KHOR GIDAD	VILLAGE	29	SOIL	Dealer Dwelling	Yard	

SAMPLE	SAMPLING		COORDINATE DD		ALT	AREA	SITE	SPOT	SAMPLE	LOCATION		ACTIVITY
N°	DATE	TIME	LAT N	LONG E	m	NAME		N°	TYPE			ZONE
SSO032	11-APR-04	17:15:38	11.41736	34.02092	742.7	KHOR GIDAD	VILLAGE	30	SOIL	Shop	Yard	Amalgamation
SSO033	11-APR-04	17:25:30	11.41736	34.02087	743.2	KHOR GIDAD	VILLAGE	31	SOIL	Shop	Yard	Amalgamation
SSO034	11-APR-04	17:59:38	11.41639	34.02122	738.2	KHOR GIDAD	VILLAGE	31	SOIL	Shop	Yard	
SSO035	11-APR-04	18:06:09	11.41649	34.02123	738.2	KHOR GIDAD	VILLAGE	32	SOIL	Shop	Yard	Amalgamation
SSO036	11-APR-04	18:10:12	11.41706	34.02111	741.3	KHOR GIDAD	VILLAGE	32	SOIL	Shop	Yard	
SSO037	12-APR-04	10:22:12	11.41716	34.02118	736.0	KHOR GIDAD	VILLAGE	33	SOIL	Shop	Yard	Amalgamation
SSO038	12-APR-04	10:37:04	11.41705	34.02115	737.0	KHOR GIDAD	VILLAGE	33	SOIL	Shop	Yard	Amalgamation
SSO039	12-APR-04	10:53:05	11.41898	34.02030	735.3	KHOR GIDAD	VILLAGE	33	SOIL	Shop	Yard	
SSO040	12-APR-04	10:57:58	11.41898	34.02029	740.6	KHOR GIDAD	VILLAGE	34	SOIL	Dealer Dwelling	Yard	Amalgamation
SSO041	12-APR-04	11:08:36	11.41895	34.02027	741.8	KHOR GIDAD	VILLAGE	34	SOIL	Dealer Dwelling	Yard	Amalgamation
SSO042	12-APR-04	11:13:22	11.41898	34.02029	747.1	KHOR GIDAD	VILLAGE	34	SOIL	Dealer Dwelling	Yard	Amalgamation
SSO043	12-APR-04	12:22:42	11.41975	34.01911	740.6	KHOR GIDAD	VILLAGE	34	SOIL	Dealer Dwelling	Hut	
SSO044	12-APR-04	12:36:49	11.41963	34.02037	746.6	KHOR GIDAD	MINING	35	SOIL	Miner Dwelling	Yard	
SSO045	12-APR-04	12:39:10	11.41961	34.02033	746.8	KHOR GIDAD	MINING	36	SOIL	Miner Dwelling	Yard	
SSO046	12-APR-04	15:07:10	11.41607	34.02163	747.8	KHOR GIDAD	MINING	36	SOIL	Miner Dwelling	Yard	
SSO047	12-APR-04	15:17:42	11.41608	34.02170	733.1	KHOR GIDAD	VILLAGE	39	SOIL	Miner Dwelling	Yard	Amalgamation
SSO048	12-APR-04	15:31:47	11.41565	34.02207	740.3	KHOR GIDAD	VILLAGE	39	SOIL	Miner Dwelling	Yard	
SSO049	12-APR-04	15:39:24	11.41314	34.02101	738.7	KHOR GIDAD	VILLAGE	39	SOIL	Garden	Garden	
SSO050	14-APR-04	10:31:57	11.41309	34.02102	739.9	KHOR GIDAD	VILLAGE	47	SOIL	Miner Dwelling	Yard	Amalgamation
SSO051	14-APR-04	10:42:26	11.41311	34.02105	740.3	KHOR GIDAD	VILLAGE	47	SOIL	Miner Dwelling	Yard	Amalgamation
SSO052	14-APR-04	10:56:13	11.41285	34.02127	735.5	KHOR GIDAD	VILLAGE	47	SOIL	Miner Dwelling	Yard	Reference
SSO053	14-APR-04	12:31:07	11.41586	34.02277	743.2	KHOR GIDAD	VILLAGE	47	SOIL	Garden	Garden	
SSO054	14-APR-04	16:03:55	11.41811	34.02077	732.6	KHOR GIDAD	VILLAGE	51	SOIL	Garden	Garden	Reference
SSO055	14-APR-04	16:07:26	11.41813	34.02069	745.9	KHOR GIDAD	MINING	52	SOIL	Miner Dwelling	Yard	
SSO056	14-APR-04	11:15:56	11.37424	34.01706	741.1	KHOR GIDAD	MINING	52	SOIL	Miner Dwelling	Yard	
SSO057	15-APR-04	11:19:12	11.37427	34.01705	791.0	GUGUB	VILLAGE	64	SOIL	Family unit	Yard	Amalgamation
SSO058	15-APR-04	11:23:55	11.37430	34.01705	792.0	GUGUB	VILLAGE	64	SOIL	Family unit	Yard	Amalgamation
SSO059	15-APR-04	11:25:14	11.37429	34.01706	789.8	GUGUB	VILLAGE	64	SOIL	Family unit	Yard	Amalgamation
SSO060	15-APR-04	11:38:16	11.37333	34.01574	792.2	GUGUB	VILLAGE	64	SOIL	Family unit	Yard	Amalgamation
SSO061	15-APR-04	11:40:47	11.37329	34.01572	802.1	GUGUB	VILLAGE	65	SOIL	Family unit	Yard	
SSO062	15-APR-04	11:42:37	11.37336	34.01578	795.4	GUGUB	VILLAGE	65	SOIL	Family unit	Yard	

SAMPLE	SAMPLING		COORDINATE DD		ALT	AREA	SITE	SPOT	SAMPLE	LOCATION		ACTIVITY
N°	DATE	TIME	LAT N	LONG E	m	NAME		N°	TYPE			ZONE
SSO063	15-APR-04	11:43:42	11.38840	34.05509	796.1	GUGUB	VILLAGE	65	SOIL	Family unit	Yard	
SSO064	15-APR-04	13:32:47	11.38842	34.05509	715.6	TAGA	VILLAGE	66	SOIL	Family unit	Yard	Reference
SSO065	15-APR-04	13:35:40	11.38840	34.05524	713.7	TAGA	VILLAGE	66	SOIL	Family unit	Yard	Reference
SSO066	15-APR-04	16:30:19	11.37367	34.01676	715.3	TAGA	VILLAGE	66	SOIL	Family unit	Garden	Reference

SAMPLE N°	Description
SSO001	reddish fine soil with beige bed (1 cm) - possible ancient tailings
SSO002	fine to coarse reddish soil around roasting hut , close to bedrock
SSO003	reddish coarse to fine soil close to bedrock around fire places
SSO004	garden of dry maize located 25 m away on the slope
SSO005	fine to coarse reddish soil around amalgamation area
SSO006	fine to coarse reddish soil around roasting hut , close to tailings heaps
SSO007	brown coarse soil on main amalgamation area; visible Hg droplets and gold specks after panning, visible galena and arsenopyrite
SSO008	soil from garden of dry maize located 25 m away on the slope, tailings visible in the garden
SSO009	reddish vegetal mottled soil; school could be considered as a reference point without Hg use in the village
SSO010	reddish soil in front of the mosque; mosque considered as the top point of the village centre
SSO011	trench in garden across surface drainage coming from the main amalgamation site located 25 m away
SSO012	mottled rocky soil, close to bedrock
SSO013	reddish coarsed to fine soil
SSO014	trench in a garden across surface drainage coming from the main amalgamation site located farther away
SSO015	trench in a garden across surface drainage coming from the main amalgamation site located farther away
SSO016	coarse reddish soil on cross section
SSO017	fine to coarse reddish soil; panning indicates one Hg drop and mercury associated with fine in suspension (!?)
SSO018	rocky coarse brown soil
SSO019	mottled brown soil - group of dwellings outside and above main village, on slope, strong Hg activity, visible Hg droplets in panning concentrate but no gold
SSO020	mottled brown soil - bedrock (sloping), visible Hg
SSO021	reddish coarse to fine soil close to bedrock around the roasting hut
SSO022	medium-grained reddish soil in a terrace cultivation located along the superficial drainage of the enclosure
SSO023	reddish fine to coarse soil
SSO024	reddish fine to coarse soil
SSO025	reddish fine to coarse soil
SSO026	reddish fine-grained soil, ash on top
SSO027	reddish fine-grained soil
SSO028	reddish fine-grained soil
SSO029	reddish fine-grained soil (reference)
SSO030	reddish fine to coarse soil, several Hg droplets in panning concentrate, Hg + fine sediment suspension (?)
SSO031	reddish fine-grained soil
SSO032	reddish fine-grained soil around main hut

SAMPLE N°	Description
SSO033	reddish fine-grained soil
SSO034	reddish fine-grained soil
SSO035	brown to reddish fine grained soil, visible Hg droplets in the soil without panning
SSO036	reddish fine-grained soil
SSO037	reddish fine-grained soil
SSO038	reddish fine-grained soil, enclosure dedicated to amalgamation
SSO039	reddish fine-grained soil
SSO040	reddish fine-grained soil, around hut
SSO041	reddish fine-grained soil, around hut
SSO042	reddish fine-grained soil, around hut
SSO043	mixture of soil and dust in the living hut
SSO044	red fine soil, quite new hut (no roasting, no amalgamation
SSO045	red fine soil, quite new hut (no roasting, no amalgamation
SSO046	red fine soil, quite new hut (no roasting, no amalgamation
SSO047	brown to black fine quartz and argillaceous soil on bedrock, visible gold nuggets in panning concentrate
SSO048	brown to black fine soil on bedrock
SSO049	brown to reddish fine to coarse argillaceous soil (Sorghum field)
SSO050	dry brown vegetal soil
SSO051	dry brown vegetal soil
SSO052	dry brown vegetal soil (outside amalgamation zone)
SSO053	brown to reddish fine to coarse argillaceous soil (Sorghum field)
SSO054	vegetal brown soil
SSO055	vegetal brown soil
SSO056	vegetal brown soil
SSO057	fine to coarse reddish soil around hut, close to bedrock
SSO058	fine to coarse reddish soil around hut, close to bedrock
SSO059	fine to coarse reddish soil around hut, close to bedrock
SSO060	fine to coarse reddish soil around hut, close to bedrock
SSO061	fine to coarse reddish soil along fence, close to bedrock, slope
SSO062	fine to coarse reddish soil along fence, close to bedrock, slope
SSO063	fine to coarse reddish soil along fence, close to bedrock, slope
SSO064	fine brown vegetal soil

SAMPLE N°	Description
SSO065	fine brown vegetal soil
SSO066	fine brown vegetal soil

Appendix 3

List of the termite-mound, tailings, and vegetable samples

SAMPLE	SAMPLING		COORDINATE DD		ALT	AREA	SITE	SPOT	SAMPLE	LOCATION		ACTIVITY
N°	DATE	TIME	LAT N	LONG E	m	NAME		N°	TYPE			ZONE
STA001	09-APR-04	08:58:46	11.37454	34.01639	787.0	GUGUB	VILLAGE	1	TAILING	Family unit	Yard	
STA002	09-APR-04	16:53:45	11.37350	34.01681	791.0	GUGUB	VILLAGE	6	TAILING	Family unit	Yard	
STA003	10-APR-04	12:02:27	11.36841	34.01588	811.5	GUGUB	VILLAGE	11	TAILING	Family unit	Garden	
STA004	11-APR-04	11:13:56	11.35979	34.02003	791.0	GUGUB	MINING	25	TAILING	Mining	Pits	Mining
STA005	11-APR-04	11:50:08	11.37042	34.03042	755.7	GUGUB	MINING	26	TAILING	Mining	Pits	Mining
STA017	15-APR-04	11:27:10	11.37436	34.01704	792.7	GUGUB	VILLAGE	64	TAILING	Family unit	Garden	Tailing
STA006	11-APR-04	16:23:21	11.41877	34.02057	738.7	KHOR GIDAD	VILLAGE	29	TAILING	Dealer Dwelling	Yard	Tailing
STA007	11-APR-04	17:34:52	11.41742	34.02098	741.1	KHOR GIDAD	VILLAGE	31	TAILING	Shop	Track	Amalgamation
STA008	12-APR-04	10:40:14	11.41706	34.02123	736.5	KHOR GIDAD	VILLAGE	33	TAILING	Shop	Yard	Tailing
STA009	12-APR-04	11:15:58	11.41894	34.02026	742.5	KHOR GIDAD	VILLAGE	34	TAILING	Dealer Dwelling	Yard	Tailing
STA010	12-APR-04	12:34:34	11.41963	34.02033	744.2	KHOR GIDAD	MINING	36	TAILING	Miner Dwelling	Yard	Tailing
STA011	12-APR-04	12:43:11	11.41966	34.02042	749.7	KHOR GIDAD	MINING	36	TAILING	Miner Dwelling	Yard	Tailing
STA012	12-APR-04	15:13:32	11.41609	34.02166	736.0	KHOR GIDAD	VILLAGE	39	TAILING	Miner Dwelling	Yard	Crushing
STA013	14-APR-04	10:39:17	11.41306	34.02103	741.1	KHOR GIDAD	VILLAGE	47	TAILING	Miner Dwelling	Yard	Tailing
STA014	14-APR-04	15:47:48	11.41856	34.01987	744.4	KHOR GIDAD	MINING	53	TAILING	Mining	Bank	Panning
STA015	14-APR-04	15:52:36	11.41866	34.01984	742.7	KHOR GIDAD	MINING	53	TAILING	Mining	Bank	Panning
STA016	14-APR-04	18:07:17	11.41590	34.02038	731.7	KHOR GIDAD	KHOR GIDAD	61	TAILING	Mining	Pit	Panning
STE001	09-APR-04	10:58:41	11.37379	34.01642	790.1	GUGUB	VILLAGE	3	HANT HILL	Family unit	Hut	
STE002	09-APR-04	11:04:38	11.37386	34.01642	789.8	GUGUB	VILLAGE	3	HANT HILL	Family unit	Yard	
STE003	09-APR-04	11:35:01	11.37386	34.01652	793.9	GUGUB	VILLAGE	3	HANT HILL	Garden	Garden	
STE004	09-APR-04	12:22:28	11.37361	34.01650	789.8	GUGUB	VILLAGE	3	HANT HILL	Garden	Garden	
STE005	10-APR-04	10:31:10	11.37092	34.01929	768.9	GUGUB	VILLAGE	10	HANT HILL	Family unit	Garden	Reference
STE006	12-APR-04	14:59:01	11.41631	34.02163	740.3	KHOR GIDAD	MINING	38	HANT HILL	Mining	Garden	Panning
STE007	14-APR-04	16:50:21	11.41648	34.02278	729.5	KHOR GIDAD	MINING	58	HANT HILL	Drainage	Bank	
STE008	14-APR-04	17:55:55	11.41988	34.02377	742.7	KHOR GIDAD	MINING	60	HANT HILL	Mining	Pit	
SVE001	09-APR-04	10:25:23	11.37390	34.01621	790.1	GUGUB	VILLAGE	2	VEGETABLE	Shop	Hut	Roasting
SVE002	09-APR-04	10:26:23	11.37390	34.01621	790.1	GUGUB	VILLAGE	2	VEGETABLE	Shop	Hut	Roasting
SVE003	09-APR-04	11:17:40	11.37385	34.01647	792.0	GUGUB	VILLAGE	3	VEGETABLE	Family unit	Hut	Roasting
SVE004	09-APR-04	11:18:40	11.37385	34.01647	792.0	GUGUB	VILLAGE	3	VEGETABLE	Family unit	Hut	Roasting
SVE005	10-APR-04	10:22:11	11.37093	34.02053	771.3	GUGUB	VILLAGE	10	VEGETABLE	Family unit	Hut	Reference
SVE006	10-APR-04	10:23:11	11.37093	34.02053	771.3	GUGUB	VILLAGE	10	VEGETABLE	Family unit	Hut	Reference
SVE007	15-APR-04	13:22:57	11.38844	34.05503	713.4	TAGA	VILLAGE	66	VEGETABLE	Family unit	Hut	Reference
SVE008	15-APR-04	13:23:57	11.38844	34.05503	713.4	TAGA	VILLAGE	66	VEGETABLE	Family unit	Hut	Reference

SAMPLE N°	Description
STA001	small heap of roasting fire ashes mixed with tailings
STA002	grey to brown tailings mainly composed of ash.
STA003	beige quartzy soil mainly composed of panning concentrate tailings , along fence
STA004	medium size quartz tailings
STA005	medium size quartz and microgabbro tailings
STA006	amalgamation tailings heaps, mixture of ground quartz and reddish argillaceous soil
STA007	mixture of soil and amalgamation residues in front of shop
STA008	fine grained amalgamation residues composed of ground quartz
STA009	fine grained amalgamation residues composed of ground quartz
STA010	crushing residues
STA011	panning residues
STA012	fine grained panning residues composed of ground quartz
STA013	fine amalgamation residues mixed with ash
STA014	alluvial panning residues (reddish argillaceous quartz mixture)
STA015	alluvial panning residues (reddish argillaceous quartz mixture)
STA016	brown coarse grained soil
STA017	fine amalgamation residues mixed with ash
STE001	mottled red soil - recent ant hill on the historical site where amalgamation started in Gugub; the house is recent, less than 1 year
STE002	mottled red soil - recent ant hill (5 days) on the historical site where amalgamation started in Gugub
STE003	mottled red soil - ant hill on the edge of a garden
STE004	mottled red soil - ant hill on the edge of a garden
STE005	mottled red soil - area supposed without amalgamation and roasting
STE006	mottled red soil , ant hill close to panning area
STE007	grey dry mottled soil
STE008	reddish dry mottled soil
SVE001	dusty smoked sorghum pieces hanging from the roof (in place from October 2003)
SVE002	dusty smoked Maize pieces hanging from the roof (in place from October 2003)
SVE003	dusty smoked sorghum pieces hanging from the roof (in place from October 2003)
SVE004	dusty smoked Maize pieces hanging from the roof (in place from October 2003)
SVE005	sorghum pieces without black dust (IT)
SVE006	maize pieces without black dust (IT)
SVE007	sorghum pieces without black dust suspended from the roof
SVE008	maize pieces without black dust suspended from the roof

Appendix 4

List of sediment samples

SAMPLE	SAMPLING		COORDINATE DD		ALT	AREA	SITE	SPOT	SAMPLE	LOCATION		ACTIVITY
N°	DATE	TIME	LAT N	LONG E	m	NAME		N°	TYPE			ZONE
SSE001	09-APR-04	17:56:11	11.37148	34.01786	776.9	GUGUB	VILLAGE	12	SEDIMENT	Drainage	Stream	
SSE002	09-APR-04	18:05:55	11.37104	34.01796	778.1	GUGUB	VILLAGE	13	SEDIMENT	Drainage	Stream	
SSE003	10-APR-04	14:10:35	11.37122	34.01649	782.2	GUGUB	K. ALYAS	14	SEDIMENT	Drainage	Stream	Panning
SSE004	10-APR-04	14:14:24	11.37118	34.01655	775.7	GUGUB	K. ALYAS	14	SEDIMENT	Drainage	Stream	Panning
SSE005	10-APR-04	14:26:05	11.37122	34.01647	779.3	GUGUB	K. ALYAS	14	SEDIMENT	Drainage	Stream	Panning
SSE006	10-APR-04	14:34:18	11.37102	34.01604	783.1	GUGUB	K. ALYAS	14	SEDIMENT	Drainage	Stream	
SSE007	10-APR-04	15:03:07	11.37116	34.01759	773.5	GUGUB	K. ALYAS	15	SEDIMENT	Drainage	Stream	
SSE008	10-APR-04	15:11:40	11.37152	34.01718	778.5	GUGUB	K. ALYAS	16	SEDIMENT	Drainage	Stream	
SSE009	10-APR-04	15:25:08	11.36987	34.01934	771.8	GUGUB	K. ALYAS	17	SEDIMENT	Drainage	Stream	Panning
SSE010	10-APR-04	15:35:27	11.36975	34.02017	768.9	GUGUB	K. ALYAS	18	SEDIMENT	Drainage	Stream	
SSE011	10-APR-04	15:47:21	11.36997	34.02172	770.1	GUGUB	K. ALYAS	19	SEDIMENT	Drainage	Stream	
SSE012	10-APR-04	16:21:27	11.36988	34.02570	756.4	GUGUB	K. SHAREBAN	20	SEDIMENT	Drainage	Stream	Panning
SSE013	10-APR-04	16:24:09	11.36989	34.02569	756.4	GUGUB	K. SHAREBAN	20	SEDIMENT	Drainage	Bank	Panning
SSE014	10-APR-04	16:25:05	11.36990	34.02570	757.4	GUGUB	K. SHAREBAN	20	SEDIMENT	Drainage	Bank	Panning
SSE015	10-APR-04	17:22:50	11.37621	34.01574	786.5	GUGUB	VILLAGE	21	SEDIMENT	Drainage	Stream	
SSE016	10-APR-04	17:31:09	11.37714	34.01635	784.8	GUGUB	VILLAGE	22	SEDIMENT	Drainage	Stream	
SSE017	10-APR-04	17:42:14	11.37817	34.01748	768.2	GUGUB	VILLAGE	23	SEDIMENT	Drainage	Stream	
SSE018	10-APR-04	17:53:51	11.37641	34.01682	778.8	GUGUB	VILLAGE	24	SEDIMENT	Drainage	Stream	
SSE019	11-APR-04	11:08:02	11.35952	34.02018	793.2	GUGUB	MINING	25	SEDIMENT	Drainage	Stream	Mining
SSE020	11-APR-04	12:09:33	11.36444	34.02109	769.7	GUGUB	MINING	26	SEDIMENT	Mining	Stream	Mining
SSE021	12-APR-04	12:51:29	11.41989	34.02062	743.7	KHOR GIDAD	MINING	36	SEDIMENT	Miner Dwelling	Stream	
SSE022	12-APR-04	13:06:31	11.41840	34.02156	743.0	KHOR GIDAD	MINING	37	SEDIMENT	Drainage	Stream	
SSE023	13-APR-04	07:50:59	11.76021	34.37371	479.6	ROSEIRES	DAM	40	SEDIMENT	Dam	Bank	Fishing
SSE024	13-APR-04	07:57:27	11.76052	34.37346	476.9	ROSEIRES	DAM	40	SEDIMENT	Dam	Bank	Fishing
SSE025	13-APR-04	08:48:14	11.69051	34.33598	479.8	ROSEIRES	DAM	41	SEDIMENT	Dam	Bank	Fishing
SSE026	13-APR-04	08:51:26	11.69032	34.33598	479.6	ROSEIRES	DAM	41	SEDIMENT	Dam	Bank	Fishing
SSE027	13-APR-04	10:06:57	11.61800	34.31837	483.7	ROSEIRES	W.MAGANZA	42	SEDIMENT	Pool	Stream	
SSE028	13-APR-04	10:16:50	11.61788	34.31810	480.8	ROSEIRES	W.MAGANZA	42	SEDIMENT	Pool	Bank	
SSE029	13-APR-04	11:00:39	11.58692	34.30362	492.6	ROSEIRES	W.MAGANZA	43	SEDIMENT	Drainage	Stream	
SSE030	13-APR-04	11:04:37	11.58693	34.30358	492.1	ROSEIRES	W.MAGANZA	43	SEDIMENT	Drainage	Bank	
SSE031	13-APR-04	19:01:08	11.46732	34.16645	589.9	ROSEIRES	W.MAGANZA	44	SEDIMENT	Drainage Torrent	Stream	

SAMPLE	SAMPLING		COORDINATE DD		ALT	AREA	SITE	SPOT	SAMPLE	LOCATION		ACTIVITY
N°	DATE	TIME	LAT N	LONG E	m	NAME		N°	TYPE			ZONE
SSE032	13-APR-04	19:04:59	11.46728	34.16658	591.1	ROSEIRES	W.MAGANZA	44	SEDIMENT	Drainage Torrent	Bank	
SSE033	14-APR-04	09:48:58	11.38314	34.01795	761.5	GUGUB	KHOR ?	45	SEDIMENT	Drainage Torrent	Stream	
SSE034	14-APR-04	10:01:08	11.38527	34.01671	753.6	GUGUB	KHOR ?	46	SEDIMENT	Drainage Torrent	Stream	
SSE035	14-APR-04	10:05:33	11.38530	34.01663	759.3	GUGUB	KHOR ?	46	SEDIMENT	Drainage Torrent	Stream	
SSE036	14-APR-04	11:03:13	11.41313	34.02138	734.6	KHOR GIDAD	VILLAGE	47	SEDIMENT	Drainage	Stream	
SSE037	14-APR-04	11:10:41	11.41268	34.02216	734.3	KHOR GIDAD	VILLAGE	47	SEDIMENT	Drainage	Stream	Reference
SSE038	14-APR-04	11:42:27	11.41426	34.02369	727.4	KHOR GIDAD	KHOR GIDAD	48	SEDIMENT	Drainage	Stream	Panning
SSE039	14-APR-04	11:57:42	11.41520	34.02415	728.6	KHOR GIDAD	KHOR GIDAD	49	SEDIMENT	Drainage	Stream	Panning
SSE040	14-APR-04	12:08:34	11.41483	34.02491	728.8	KHOR GIDAD	KHOR GIDAD	50	SEDIMENT	Drainage	Stream	Panning
SSE041	14-APR-04	15:11:46	11.42010	34.01612	742.5	KHOR GIDAD	MINING	54	SEDIMENT	Mining	Pit	Panning
SSE042	14-APR-04	15:28:22	11.41884	34.01873	742.5	KHOR GIDAD	MINING	54	SEDIMENT	Drainage	Stream	Panning
SSE043	14-APR-04	16:17:32	11.41805	34.02134	743.5	KHOR GIDAD	MINING	55	SEDIMENT	Drainage	Bank	
SSE044	14-APR-04	16:29:48	11.41807	34.02137	738.7	KHOR GIDAD	MINING	56	SEDIMENT	Drainage	Stream	
SSE045	14-APR-04	16:36:32	11.41737	34.02248	737.9	KHOR GIDAD	MINING	57	SEDIMENT	Drainage	Bank	
SSE046	14-APR-04	16:59:09	11.41636	34.02294	736.5	KHOR GIDAD	KHOR GIDAD	59	SEDIMENT	Drainage	Stream	
SSE047	14-APR-04	18:40:29	11.37873	34.03216	730.0	GUGUB	W.ABU DJAL	61	SEDIMENT	Drainage	Stream	Panning
SSE048	15-APR-04	09:55:05	11.38106	34.00716	797.8	GUGUB	STREAM	62	SEDIMENT	Pool	Stream	Fishing
SSE049	15-APR-04	10:16:10	11.38425	34.00890	780.7	GUGUB	STREAM	63	SEDIMENT	Pool	Stream	Fishing

SAMPLE N°	Description
SSE001	fine brown dry sediment downstream south of the village
SSE002	fine brown dry sediment with black organic matter layers downstream south of the village (Khor Alyas)
SSE003	fine brown dry sediment
SSE004	fine brown dry sediment (galena specks)
SSE005	fine brown dry sediment rich in organic matter (mm-size black layers)
SSE006	fine brown dry sediment
SSE007	fine brown dry sediment rich in organic matter (mm-size black layers)
SSE008	fine brown dry sediment
SSE009	fine brown dry sediment rich in organic matter (mm-size black layers)
SSE010	fine brown dry sediment
SSE011	fine brown dry sediment
SSE012	stream gravels sediment (dry)
SSE013	fine brown dry sediment rich in organic matter (mm-size black layers)
SSE014	fine brown dry sediment rich in organic matter (mm-size black layers)
SSE015	fine brown dry sediment rich in organic matter (mm-size black layers)
SSE016	medium to fine homogeneous sediment
SSE017	medium to fine homogeneous sediment
SSE018	medium to fine homogeneous sediment with black beds (OM)
SSE019	medium to fine homogeneous sediment
SSE020	fine brown sediment
SSE021	brown to reddish fine sediment with vegetal debris, stream close to previous samples
SSE022	brown fine sediment with vegetal debris
SSE023	wet black MO-rich fine mud or muck
SSE024	wet black MO-rich fine mud or muck
SSE025	wet black MO-rich fine mud or muck
SSE026	wet black sand-rich fine mud or muck
SSE027	wet black MO-rich fine mud or muck
SSE028	dry black MO-rich fine mud (flood deposit)
SSE029	dry coarse-grained sandy sediment
SSE030	dry black MO-rich fine mud (flood deposit)
SSE031	dry coarse-grained sandy sediment (large wadi , 50m)

SAMPLE N°	Description
SSE032	dry black MO-rich fine mud (flood deposit)
SSE033	dry fine to medium grained black sediment
SSE034	dry fine to medium grained black sediment
SSE035	dry black MO-rich fine mud (flood deposit)
SSE036	fine brown sediments
SSE037	brown sediments poor in fine particles
SSE038	coarse-grained quartzy sediment
SSE039	coarse-grained quartzy sediment
SSE040	coarse-grained quartzy sediment
SSE041	fine black clay in the upper part of a pit
SSE042	coarse-grained quartzy sediment
SSE043	fine black clay on "inselbergs"
SSE044	coarse-grained quartzy sediment
SSE045	coarse-grained quartzy sediment
SSE046	coarse-grained quartzy sediment
SSE047	consolidated fine brown sediment
SSE048	wet black sand-rich fine mud or muck
SSE049	wet black sand-rich fine mud or muck

Appendix 5

Description of fish samples

Family	Genus	Species	Habitat	Food regime	Feeding details	Fish number				Total Number
						Roseires			Gugub	
						1	2	3	4	
Clariidae	Clarias	gariepinus	benthopelagic	benthivorous	bottom feeder: insects invertebrates, fish, rotting flesh and plants	**5**	**4**		**1**	**10**
Cichlidae	Oreochromis	niloticus	demersal	herbivorous	phytoplankton, benthic algae			**5**	**14**	**19**
Cichlidae	Sarotherodon	galilaeus	demersal	herbivorous	algae and fine organic debris	**6**	**5**			**11**
Schilbeidae	Schilbe	intermedius	pelagic	carnivorous	Invertebrates including terrestrial insects, fish	**5**		**4**		**9**
Alestiidae	Hydrocinus	forskalii	pelagic	carnivorous	fish, insects	**5**				**5**
Alestiidae	Brycinus	nurse	pelagic	omnivorous	zooplankton, shrimp, insects, vegetation	**5**				**5**
Centropomidae	Lates	niloticus	demersal	carnivorous	fish, shrimp	**6**				**6**
Cyprinidae	Labeo	niloticus	demersal	benthivorous	bottom feeder, vegetarian, epilithic algae	**5**			**14**	**19**
Mormyridae	Mormyrus	niloticus	pelagic	carnivorous	insects, invertebrates			**2**		**2**
Mormyridae	Hyperopisus	bebe	demersal	omnivorous	plankton, molluscs, aquatic insects			**2**		**2**
Mormyridae	Marcusenius	senegalensis	demersal	insectivorous				**2**		**2**
Mochokidae	Synondontis	schall	benthopelagic	omnivorous	invertebrates, fish, molluscs		**6**	**6**		**12**
Bagridae	Auchenoglanis	occidentalis	demersal	omnivorous	plankton, insects, molluscs, seeds and detritus			**2**		**2**
Unidentified species									**4**	**4**
					Total	**37**	**15**	**23**	**33**	**108**

DESCRIPTION OF THE FISH SAMPLE

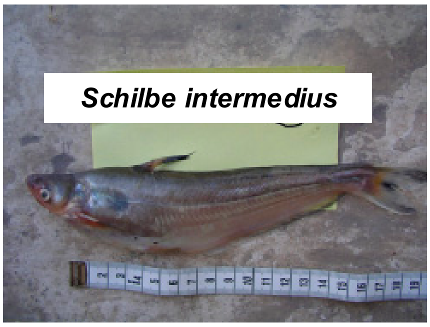
PHOTOGRAPHS OF FISH SPECIES COLLECTED

FROM THE DIFFERENT FISHING SPOTS

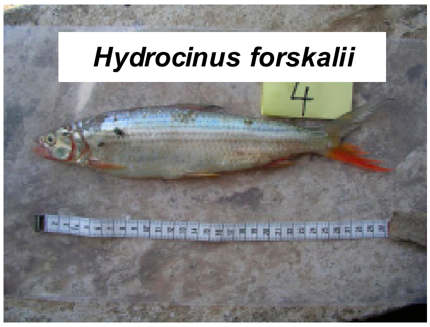
(x: undetermined fish species)

Clarias gariepinus

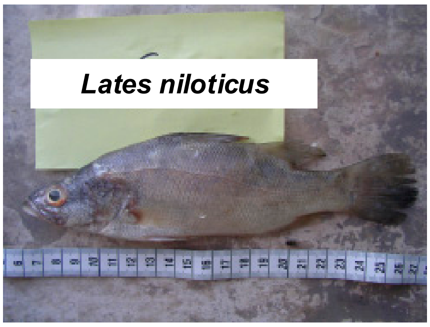
Sarotherodon galilaeus



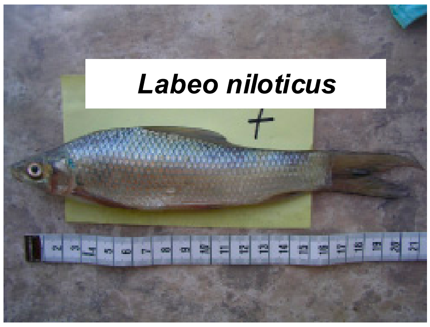
Schilbe intermedius



Hydrocinus forskalii

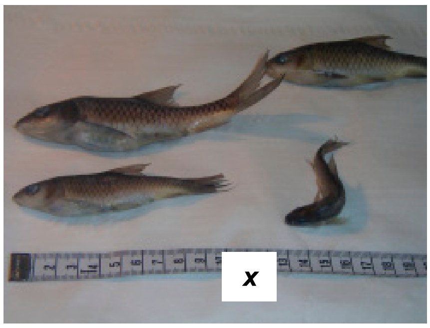


Lates niloticus

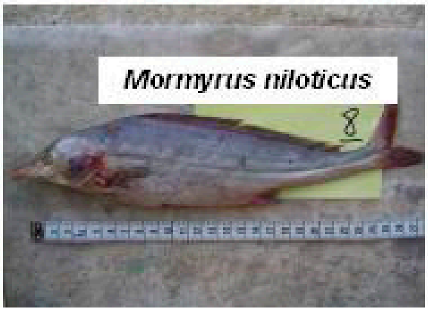


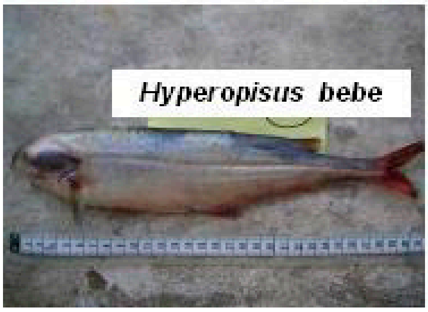
Labeo niloticus

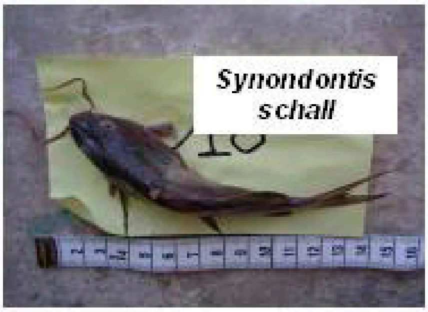
Labeo horie

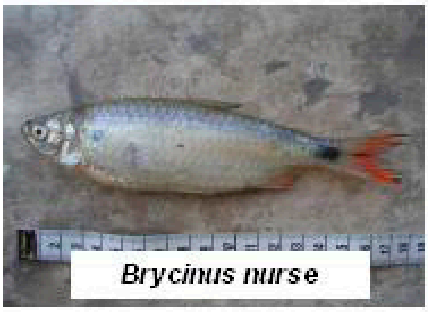


x

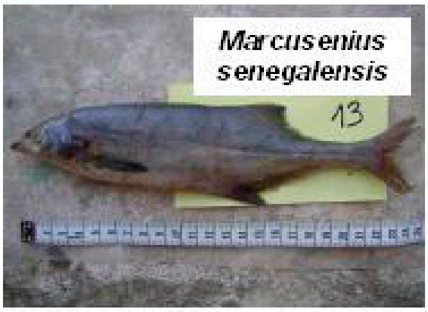

Mormyrus niloticus

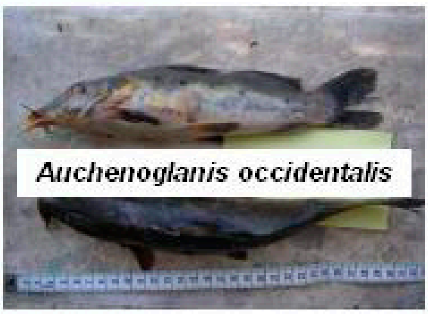

Hyperopisus bebe


Synondontis
schall


Brycinus nurse


Sarotherodon galilaeus


Marcusenius
senegalensis

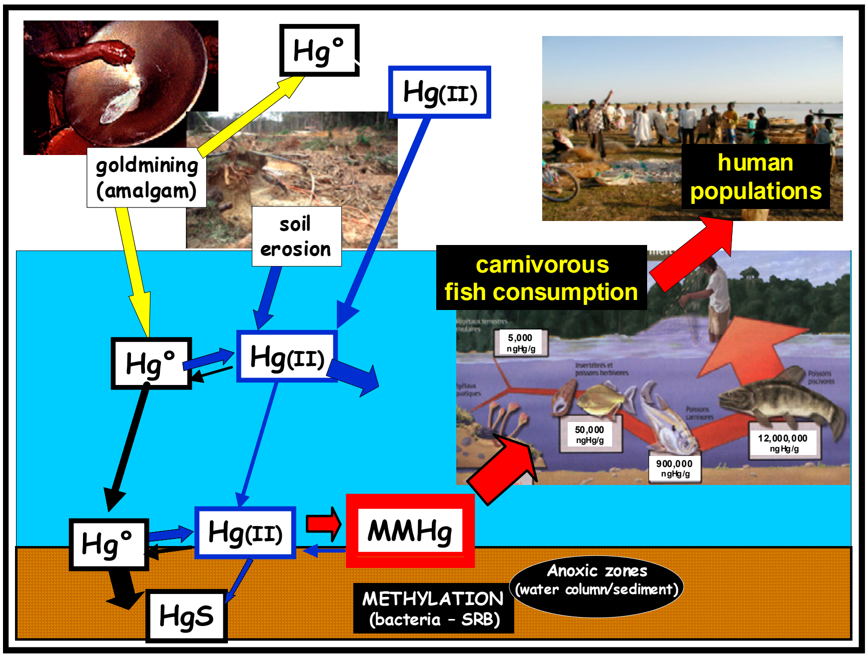

Auchenoglanis occidentalis

BIOMETRIC DATA AND MERCURY CONCENTRATIONS MEASURED IN INDIVIDUAL FISH SPECIMENS (N=108)

Family	Genus	Species	Food regime	Standard length (cm)	Body weight (g, fw)	Hg conc (µg/g, dw)	Sampling spot
Clariiidae	*Clarias*	*gariepinus*	benthivorous	19.5	60	0.062	1
Clariiidae	*Clarias*	*gariepinus*	benthivorous	18.0	54	0.099	1
Clariiidae	*Clarias*	*gariepinus*	benthivorous	22.0	108	0.122	1
Clariiidae	*Clarias*	*gariepinus*	benthivorous	18.5	66	0.070	1
Clariiidae	*Clarias*	*gariepinus*	benthivorous	20.5	96	0.073	1
Schilbeidae	*Schilbe*	*intermedius*	carnivorous	17.0	54	0.569	1
Schilbeidae	*Schilbe*	*intermedius*	carnivorous	18.0	76	0.514	1
Schilbeidae	*Schilbe*	*intermedius*	carnivorous	17.0	56	0.460	1
Schilbeidae	*Schilbe*	*intermedius*	carnivorous	14.0	32	0.266	1
Schilbeidae	*Schilbe*	*intermedius*	carnivorous	12.0	18	0.217	1
Alestiidae	*Hydrocinus*	*forskalii*	carnivorous	19.3	88	0.894	1
Alestiidae	*Hydrocinus*	*forskalii*	carnivorous	26.5	190	0.698	1
Alestiidae	*Hydrocinus*	*forskalii*	carnivorous	22.5	128	0.701	1
Alestiidae	*Hydrocinus*	*forskalii*	carnivorous	17.5	64	0.426	1
Alestiidae	*Hydrocinus*	*forskalii*	carnivorous	20.5	112	0.751	1
Centropomidae	*Lates*	*niloticus*	carnivorous	15.0	64	0.713	1
Centropomidae	*Lates*	*niloticus*	carnivorous	17.0	94	0.539	1
Centropomidae	*Lates*	*niloticus*	carnivorous	13.0	42	0.783	1
Centropomidae	*Lates*	*niloticus*	carnivorous	13.7	54	0.677	1
Centropomidae	*Lates*	*niloticus*	carnivorous	13.3	46	0.629	1
Centropomidae	*Lates*	*niloticus*	carnivorous	12.5	34	0.907	1
Cyprinidae	*Labeo*	*niloticus*	benthivorous	16.0	66	0.048	1
Cyprinidae	*Labeo*	*niloticus*	benthivorous	15.0	52	0.078	1
Cyprinidae	*Labeo*	*niloticus*	benthivorous	17.0	74	0.051	1
Cyprinidae	*Labeo*	*niloticus*	benthivorous	14.5	52	0.049	1
Cyprinidae	*Labeo*	*niloticus*	benthivorous	15.5	64	0.054	1
Alestiidae	*Brycinus*	*nurse*	omnivorous	13.0	46	0.081	1
Alestiidae	*Brycinus*	*nurse*	omnivorous	13.5	52	0.121	1
Alestiidae	*Brycinus*	*nurse*	omnivorous	14.0	56	0.122	1
Alestiidae	*Brycinus*	*nurse*	omnivorous	13.0	52	0.141	1
Alestiidae	*Brycinus*	*nurse*	omnivorous	13.0	50	0.072	1
Cichlidae	*Sarotherodon*	*galilaeus*	herbivorous	9	22	0.154	1
Cichlidae	*Sarotherodon*	*galilaeus*	herbivorous	9	24	0.104	1
Cichlidae	*Sarotherodon*	*galilaeus*	herbivorous	9	24	0.092	1
Cichlidae	*Sarotherodon*	*galilaeus*	herbivorous	9	22	0.124	1
Cichlidae	*Sarotherodon*	*galilaeus*	herbivorous	9.2	28	0.131	1
Cichlidae	*Sarotherodon*	*galilaeus*	herbivorous	8.7	24	0.072	1
Clariiidae	*Clarias*	*gariepinus*	benthivorous	35.0	430	0.167	2
Clariiidae	*Clarias*	*gariepinus*	benthivorous	38.0	622	0.039	2
Clariiidae	*Clarias*	*gariepinus*	benthivorous	43.0	630	0.061	2
Clariiidae	*Clarias*	*gariepinus*	benthivorous	40.5	540	0.127	2
Cichlidae	*Sarotherodon*	*galilaeus*	herbivorous	18.0	180	0.110	2
Cichlidae	*Sarotherodon*	*galilaeus*	herbivorous	16.0	142	0.169	2
Cichlidae	*Sarotherodon*	*galilaeus*	herbivorous	18.5	204	0.051	2
Cichlidae	*Sarotherodon*	*galilaeus*	herbivorous	16.0	138	0.112	2
Cichlidae	*Sarotherodon*	*galilaeus*	herbivorous	16.0	154	0.082	2
Mochokidae	*Synondontis*	*schall*	omnivorous	10.5	26	0.518	2
Mochokidae	*Synondontis*	*schall*	omnivorous	11.5	34	0.582	2
Mochokidae	*Synondontis*	*schall*	omnivorous	10.0	22	0.224	2
Mochokidae	*Synondontis*	*schall*	omnivorous	9.0	14	0.119	2
Mochokidae	*Synondontis*	*schall*	omnivorous	9.0	14	0.157	2
Mochokidae	*Synondontis*	*schall*	omnivorous	7.5	10	0.112	2

Family	Genus	Species	Food regime	Standard length (cm)	Body weight (g, fw)	Hg conc (µg.g-1 dw)	Sampling spot
Cichlidae	Oreochromis	niloticus	herbivorous	22.0	346	0.105	3
Cichlidae	Oreochromis	niloticus	herbivorous	20.0	244	0.069	3
Cichlidae	Oreochromis	niloticus	herbivorous	20.5	256	0.049	3
Cichlidae	Oreochromis	niloticus	herbivorous	20.0	232	0.083	3
Cichlidae	Oreochromis	niloticus	herbivorous	19.0	254	0.093	3
Schilbeidae	Schilbe	intermedius	carnivorous	24.0	132	0.308	3
Schilbeidae	Schilbe	intermedius	carnivorous	25.0	140	0.517	3
Schilbeidae	Schilbe	intermedius	carnivorous	22.0	124	0.677	3
Schilbeidae	Schilbe	intermedius	carnivorous	22.5	138	0.655	3
Mormyridae	Mormyrus	niloticus	carnivorous	23.0	106	0.100	3
Mormyridae	Mormyrus	niloticus	carnivorous	25.0	138	0.096	3
Mormyridae	Hyperopisus	bebe	omnivorous	27.0	184	0.107	3
Mormyridae	Hyperopisus	bebe	omnivorous	28.0	194	0.077	3
Mochokidae	Synondontis	schall	omnivorous	17.0	96	0.062	3
Mochokidae	Synondontis	schall	omnivorous	13.0	48	1.039	3
Mochokidae	Synondontis	schall	omnivorous	14.0	70	0.519	3
Mochokidae	Synondontis	schall	omnivorous	13.0	56	0.417	3
Mochokidae	Synondontis	schall	omnivorous	13.5	64	0.670	3
Mochokidae	Synondontis	schall	omnivorous	15.0	62	0.977	3
Mormyridae	Marcusenius	senegalensis	carnivorous	22.0	112	0.080	3
Mormyridae	Marcusenius	senegalensis	carnivorous	20.0	98	0.126	3
Bagridae	Auchenoglanis	occidentalis	omnivorous	24.0	256	0.046	3
Bagridae	Auchenoglanis	occidentalis	omnivorous	22.0	198	0.057	3
Clariidae	Clarias	gariepinus	benthivorous	22.0	69	0.243	4
Cichlidae	Oreochromis	niloticus	herbivorous	5.0	4	0.041	4
Cichlidae	Oreochromis	niloticus	herbivorous	5.0	4	0.047	4
Cichlidae	Oreochromis	niloticus	herbivorous	4.0	2	0.056	4
Cichlidae	Oreochromis	niloticus	herbivorous	7.9	13	0.056	4
Cichlidae	Oreochromis	niloticus	herbivorous	5.6	6	0.069	4
Cichlidae	Oreochromis	niloticus	herbivorous	5.0	6	0.056	4
Cichlidae	Oreochromis	niloticus	herbivorous	7.0	12	0.075	4
Cichlidae	Oreochromis	niloticus	herbivorous	6.3	9	0.032	4
Cichlidae	Oreochromis	niloticus	herbivorous	7.5	15	0.072	4
Cichlidae	Oreochromis	niloticus	herbivorous	8.0	19	0.059	4
Cichlidae	Oreochromis	niloticus	herbivorous	8.0	21	0.064	4
Cichlidae	Oreochromis	niloticus	herbivorous	9.0	23	0.055	4
Cichlidae	Oreochromis	niloticus	herbivorous	9.5	33	0.065	4
Cichlidae	Oreochromis	niloticus	herbivorous	10.5	39	0.049	4
Cichlidae	Oreochromis	niloticus	herbivorous	10.5	40	0.054	4
Cyprinidae	labeo	horie	benthivorous	6.5	4	0.099	4
Cyprinidae	labeo	horie	benthivorous	6.0	5	0.103	4
Cyprinidae	labeo	horie	benthivorous	11.0	22	0.325	4
Cyprinidae	labeo	horie	benthivorous	9.0	13	0.225	4
Cyprinidae	labeo	horie	benthivorous	10.0	14	0.109	4
Cyprinidae	labeo	horie	benthivorous	11.5	25	0.666	4
Cyprinidae	labeo	horie	benthivorous	12.0	40	0.075	4
Cyprinidae	labeo	horie	benthivorous	11.5	26	0.082	4
Cyprinidae	labeo	horie	benthivorous	9.5	16	0.102	4
Cyprinidae	labeo	horie	benthivorous	11.5	30	0.198	4
Cyprinidae	labeo	horie	benthivorous	14.0	47	0.109	4
Cyprinidae	labeo	horie	benthivorous	11.0	20	0.174	4
Cyprinidae	labeo	horie	benthivorous	5.0	2	0.246	4
Cyprinidae	labeo	horie	benthivorous	7.0	6	0.204	4
x	x	x	x	9.0	13	0.227	4
x	x	x	x	10.0	18	0.208	4
x	x	x	x	12.0	30	0.682	4
x	x	x	x	16.0	45	0.227	4

MAIN BIOGEOCHEMICAL STEPS BETWEEN GOLDMINING USING THE AMALGAMATION PROCEDURE AND HUMAN POPULATION EXPOSURE, VIA THE INGESTION OF CARNIVOROUS FISH SPECIES AT THE TOP OF THE AQUATIC FOODCHAIN (FROM BOUDOU, 2004).



Fish are exposed to mercury present in the aquatic system, either through passive (respiratory) exposure or through the diet (Snodgrass, Jagoe et al., 2000), where contamination levels in the water column are generally very low, close to the ppt level (ngHg/L), and consist mainly of the inorganic form (HgII). Thus, the trophic route of exposure, *via* ingestion of the metal accumulated in prey and absorption through the intestinal wall, represents the major contamination source for the different fish species, with biomagnification playing a key role along the aquatic food chain (Boudou & Ribeyre, 1997; Mason et al., 1995; Wiener et al, 2002). Biomagnification is essentially based on cumulative trophic transfer of the methylated form of mercury (MMHg: monomethylmercury – CH_3HgX) between prey and predators, leading to extremely high concentrations in the different organs of carnivorous species, notably in the skeletal muscle tissue (Bloom, 1992; Boudou & Ribeyre, 1997). So, within the complex biogeochemical cycle of mercury, the elemental form Hg° used for amalgamation has to be oxidised in the atmosphere and/or in water (HgII) and then methylated by bacteria (SRB: sulphur-reducing bacteria), mainly under hypoxic/anoxic conditions (Morel et al., 1998; Rudd, 1995).

Appendix 6

Results of Hg analyses

SEDIMENTS				
	ID	PM 40° C %	Hg Results	
				double
			mg/kg	mg/kg
1	SSE001	0.88	0.133	
2	SSE002	0.96	0.225	
3	SSE003	0.62	1.649	
4	SSE004	0.53	1.46	
5	SSE005	1.00	1.066	
6	SSE006	1.42	0.221	
8	SSE007	1.15	0.14	
9	SSE008	0.95	0.132	
10	SSE009	0.87	0.276	0.283
11	SSE010	0.89	0.072	
12	SSE011	0.86	0.153	
13	SSE012	1.26	0.042	
14	SSE013	1.47	0.059	
15	SSE014	1.72	0.077	
16	SSE015	1.52	0.092	
17	SSE016	1.06	0.116	
18	SSE017	0.93	0.121	
19	SSE018	0.98	0.078	0.08
20	SSE019	1.65	0.324	
21	SSE020	3.02	0.211	
22	SSE021	1.59	0.081	
23	SSE022	1.09	0.199	
24	SSE023	53.7	0.265	
25	SSE024	67.1	0.386	
26	SSE025	24.0	0.19	
27	SSE026	23.0	0.157	
28	SSE027	49.3	0.148	
29	SSE028	12.9	0.072	
30	SSE029	2.63	0.053	0.056
31	SSE030	2.15	0.078	
32	SSE031	0.90	0.042	
33	SSE032	1.47	0.059	
34	SSE033	1.62	0.203	
35	SSE034	1.04	0.16	
36	SSE035	1.41	0.176	
37	SSE036	1.32	0.065	
38	SSE037	1.39	0.424	0.422
39	SSE038	1.50	0.12	
40	SSE039	1.29	0.101	
41	SSE040	1.04	0.087	
42	SSE041	0.88	0.176	
43	SSE042	0.79	0.048	

SEDIMENTS (Cont'd)				
	ID	PM 40° C %	Hg Results	
44	SSE043	1.29	0.077	
45	SSE044	0.98	0.886	
46	SSE045	1.06	0.163	
47	SSE046	1.31	0.118	0.118
48	SSE047	1.35	0.081	
49	SSE048	30.8	0.251	
50	SSE049	31.3	0.316	

DUST				
	ID	PM 40° C %	Hg Results	
				double
			mg/kg	mg/kg
51	SDU001	1.69	0.914	
52	SDU002	1.81	2.751	
53	SDU003	0.88	2.662	
54	SDU004	1.19	1.42	
55	SDU005	1.51	1.433	
56	SDU006	0.91	0.052	
57	SDU007	0.87	0.157	
58	SDU008	2.67	1.219	
59	SDU009	0.85	1.999	
60	SDU010	1.03	0.973	0.997
61	SDU011	1.28	0.505	
62	SDU012	1.31	0.116	
63	SDU013	1.25	0.434	
64	SDU014	1.38	1.024	
65	SDU015	0.83	1.835	
66	SDU016	1.59	1.469	
67	SDU017	1.01	3.414	
68	SDU018	1.36	7.206	
69	SDU019	3.71	3.177	
70	SDU020	1.30	0.992	0.941
71	SDU021	1.16	5.546	
72	SDU022	0.87	2.77	
73	SDU023	1.60	840	
74	SDU024	1.32	465	
75	SDU025	1.04	9.523	
76	SDU026	1.03	0.664	
77	SDU027	0.75	0.123	
78	SDU028	1.30	0.338	
79	SDU029	0.92	1.96	
80	SDU030	1.48	0.183	0.173

SOILS				
	ID	PM 40° C %	Hg Results	
				double
			mg/kg	mg/kg
88	SSO001	0.54	8.516	
89	SSO002	0.75	1.716	1.74
90	SSO003	0.81	4.966	
91	SSO004	0.90	0.312	
92	SSO005	0.96	27.626	
93	SSO006	0.78	2.53	
94	SSO007	0.90	4.209	
95	SSO008	-0.09	0.221	
96	SSO009	0.94	0.106	0.099
97	SSO010	1.04	0.648	
98	SSO011	0.87	0.213	
99	SSO012	1.58	0.868	
100	SSO013	0.91	2.585	
101	SSO014	0.92	0.133	
102	SSO015	0.83	0.142	
103	SSO016	0.75	1.012	
104	SSO017	0.79	2.574	
105	SSO018	0.95	0.083	0.091
106	SSO019	0.54	0.275	
107	SSO020	0.68	0.544	
108	SSO021	0.57	0.492	
109	SSO022	0.60	0.675	
110	SSO023	0.64	1.307	
111	SSO024	0.30	3.571	
112	SSO025	0.59	1.213	
113	SSO026	0.49	4.01	
114	SSO027	0.50	7.805	
115	SSO028	1.31	170	
116	SSO029	0.39	1.345	
117	SSO030	2.09	13.65	
118	SSO031	0.34	0.391	
119	SSO032	0.72	1.885	
120	SSO033	0.74	4.977	6.847/5.334
121	SSO034	1.02	1.779	
122	SSO035	0.77	1000	
123	SSO036	0.76	1.665	
124	SSO037	1.23	0.965	
125	SSO038	0.95	0.466	

SOILS (Cont'd)				
	ID	PM 40° C %	Hg Results	
				double
			mg/kg	mg/kg
126	SSO039	1.31	0.209	
127	SSO040	1.17	0.283	
128	SSO041	1.31	2.037	
129	SSO042	1.10	0.677	
130	SSO043	1.63	3.328	3.213
131	SSO044	0.81	0.119	
132	SSO045	1.08	0.179	
133	SSO046	1.35	0.128	
134	SSO047	0.68	0.437	
135	SSO048	1.25	0.251	
136	SSO049	0.90	0.151	
137	SSO050	1.00	1.595	
138	SSO051	0.93	1.047	
139	SSO052	0.89	0.602	
140	SSO053	0.69	0.114	0.116
141	SSO054	1.77	0.1	
142	SSO055	1.02	0.1	
143	SSO056	0.97	0.24	
144	SSO057	0.74	2.31	
145	SSO058	0.82	3.19	
146	SSO059	0.74	2.79	
147	SSO060	0.67	5.26	
148	SSO061	0.77	0.43	
149	SSO062	0.79	1.29	
150	SSO063	0.80	3.83	3.83
151	SSO064	1.03	0.09	
152	SSO065	0.99	0.12	
153	SSO066	1.22	0.11	

TAILINGS				
	ID	PM 40° C %	Hg Results	
				double
			mg/kg	mg/kg
154	STA001	1.25	1.55	
155	STA002	1.17	0.35	
156	STA003	0.89	2.63	2.7
157	STA004	1.92	0.28	
158	STA005	2.00	0.12	
159	STA006	1.69	1.02	
160	STA007	1.66	62.3	61.5
161	STA008	1.65	0.15	0.13
162	STA009	1.85	0.13	
163	STA010	2.05	0.1	
164	STA011	1.83	0.13	
165	STA012	0.72	0.1	
166	STA013	0.47	72.5	71.4
167	STA014	1.94	0.08	
168	STA015	1.97	0.07	
169	STA016	2.36	0.19	
170	STA017	1.55	1.64	1.6

TERMITE MOUNDS				
	ID	PM 40° C %	Hg Results	
				double
			mg/kg	mg/kg
81	STE001	3.07	0.315	
82	STE002	1.48	0.083	
83	STE003	1.06	0.115	
84	STE004	1.59	0.044	
7	STE006	1.43	0.072	
85	STE005	1.72	0.041	
86	STE007	1.50	0.028	
87	STE008	1.29	0.094	

Appendix 7

Quality control of Hg analyses in solid samples

QUALITY CONTROL OF LUMEX ANALYSES *VS* STANDARD REFERENCE MATERIALS (SRM):

Internal quality control

As described in the report, the LUMEX analyser was calibrated for each analytical sequence with two reference materials (one material for low mercury quantities introduced in the device and the other one for high quantities).

NIST 2711 agricultural soil: reference value 6.25 mg kg^{-1}

STSD1 (CANMET): river sediment: reference value 0.11 mg kg^{-1}.

The validity of calibration was daily checked with a third reference material: NIST 2709 in the middle of the calibration range (results for seven independant analyses of this material are given in the table below).

NIST 2709	
Reference Value	1.40±0.08 mg kg^{-1}
Measured Value	1.36±0.18 mg kg^{-1} (n=7)

1. 10% of samples has been analysed twice.
2. In a previous study, seven reference materials (soil, sediment and dust) were analysed and gave good results in comparison with reference values (see table below)

Reference Material	**Reference value (mg kg^{-1})**	**Measured value (mean n=5)**
2711	6.25 ± 0.19	6.60 ± 0.37
LKSD3	0.29 (1)	0.29 ± 0.04
STSD4	0.93 (1)	0.99 ± 0.14
JLK1	0.142 (1)	0.15 ± 0.01
jsd3	0.254 (1)	0.25 ± 0.02
2782	1.10 ± 0.19	1.17 ± 0.09
lgc6156	10.1 ± 1.6	9.9 ± 0.3

(1) indicative value

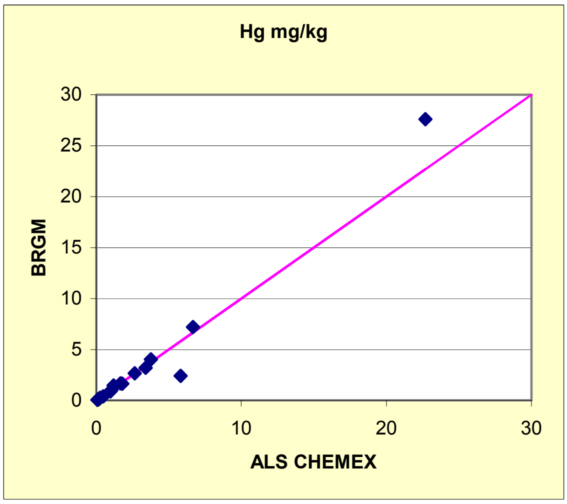
External quality control

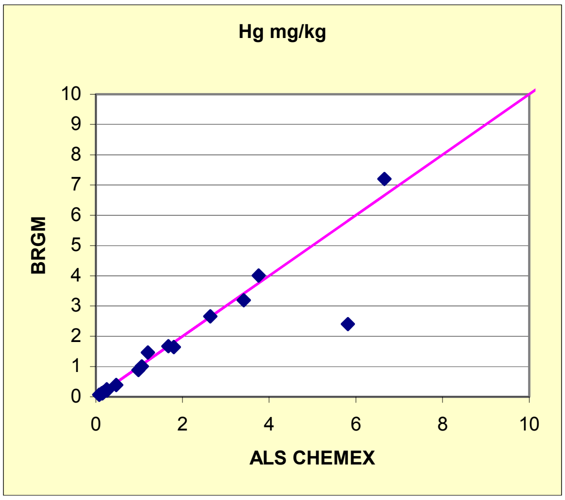
All samples collected and brought back to France were analysed with the LUMEX in the BRGM laboratory; 10% of the samples (18 samples) were selected and sent to an independent laboratory (Chemex ALS, Canada) to verify the results obtained in the BRGM laboratory with the Lumex. The analyses by Chemex ALS were performed by CV-AAS.

Sample	ALS CHEMEX CVAAS mg kg^{-1}	BRGM LUMEX mg kg^{-1}
SSE004	**1.20**	**1.46**
SSE011	**0.18**	**0.15**
SSE024	**0.47**	**0.39**
SSE036	**0.08**	**0.07**
SSE044	**0.98**	**0.89**
STA017	**1.80**	**1.64**
STE003	**0.13**	**0.12**
SDU003	**2.64**	**2.66**
SDU018	**6.66**	**7.20**
SDU025	**5.82**	**3.17**
SSO005	**22.70**	**27.60**
SSO011	**0.26**	**0.21**
SSO016	**1.06**	**1.01**
SSO026	**3.76**	**4.01**
SSO036	**1.67**	**1.67**
SSO048	**0.25**	**0.25**
SSO058	**3.41**	**3.19**
SSO066	**0.15**	**0.11**

BRGM laboratory mercury concentrations vs Chemex ALS mercury concentrations.

Comparison between Lumex and Chemex-ALS analysis for a selection of solid samples (two different scales)





The correlation between the Chemex ALS and Lumex (BRGM) results is quite good for most of samples. Only sample SDU025 (dust sample) showed a lower value by Lumex than with the reference method. It seems that this sample is rather inhomogeneous, as indicated by some repetitions done with the Lumex. This could explain the difference between the two results.

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