UN environment

Environmental assessment of mercury pollution in two artisanal gold mining sites in eastern Democratic Republic of the Congo

BUTUZI, SOUTH KIVU
SOME, ITURI

TECHNICAL REPORT FOR PARTNERSHIP AFRICA CANADA'S JUST GOLD PROJECT

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Cover Image: A piece of 'sponge' gold produced on burning of mercury-gold amalgam

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All the photos in this report were taken in Butuzi, South Kivu and Some, Ituri, except for photos 14 and 19 which were taken in Mongbwalu, Ituri.

Design and layout: Antonia Mendes and Cristina Poiata

Artisanal gold mining is degrading landscapes in eastern Democratic Republic of Congo

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Summary

This report is an environmental assessment of mercury pollution in two artisanal gold mining (AGM) sites in the eastern Democratic Republic of the Congo (DRC). It was conducted by the United Nations Environment Programme (UNEP) based on fieldwork in Butuzi, South Kivu and Some, Ituri. The purpose of this assessment is to provide technical advice to Partnership Africa Canada's (PAC) pioneering 'Just Gold' project, which aims to bring legal, conflict-free, and traceable gold from the two aforementioned artisanal mine sites to international markets. In this respect, technical assistance on mercury reduction resulting in increased gold production is also an integral component of the incentive-based model that PAC's project aims to develop to encourage artisanal producers to sell their gold through legal channels.

This study represents the first field assessment of mercury use, emissions and releases to the environment by the artisanal gold mining sector in the DRC. The methodology for preparing the inventory of emissions and releases at the two artisanal gold mining sites complies with guidance developed by the UNEP Global Mercury Partnership for the Minamata Convention on Mercury. In particular, the baseline estimates from this study should help inform the preparation of the DRC's Minamata Initial Assessment (MIA) and National Action Plan on Artisanal and Small Scale Gold Mining (NAP)[1]. In addition, the report addresses other environmental problems and associated health and occupational risks at the two aforementioned AGM sites, as well as some of the broader governance challenges facing the artisanal gold mining sector.

In addressing the multiple environmental challenges at the two AGM sites, a progressive strategy taking into account investment costs and the complexity of measures is proposed. It comprises of targeted technical interventions to:

i) reduce mercury use and pollution;
ii) help mitigate slope destabilization, deforestation and biodiversity loss; and
iii) improve occupational safety in the mining sites.

Snapshot of Artisanal Gold Mining in eastern DRC

- 80% of all artisanal miners in eastern DRC dig for gold
- An estimated 160,000-200,000 gold miners
- ~1,000 AGM sites in eastern DRC (IPIS: 857; BGR: 1305)
- AGM production estimated at 8-10 tonnes per annum
- Official exports around ~200 Kgs (i.e. 98% smuggled)
- Gold is the main resource financing armed and criminal groups in eastern DRC, accounting for 50% of profits

Source: *IPIS (2015): Mapping Conflict Minerals in Eastern DRC; UNEP-MONUSCO-OSESG (2015); Experts' background report on illegal exploitation and trade in natural resources*

[1] The DRC MIA-NAP will be implemented with technical assistance from UNEP and UNITAR, and financial support from the Global Environment Facility. Project activities are planned to start in end 2016.

Mercury pollution

Mercury use by artisanal gold miners is widespread in eastern DRC, and there is little knowledge among users about the toxicity and environmental hazards it can produce. Extensive use of mercury stems from its quick, easy and effective separation of gold from the ore. Significant mercury concentrations can be found in soil and rivers near mine sites, as well as inside homes and businesses where mercury is burned. The greatest health risk for miners, women, and children is from open amalgam burning in small communities and kitchens, as well as in urban centres.

Few of those encountered during the field assessment (miners, government officials, gold buyers) seemed to have previous awareness of the health dangers of mercury. Moreover, no one was aware that gold buyers in cities release mercury when smelting and purifying the gold. Mercury is likely evaporated when the sponge gold is melted into ingots.

Atmospheric mercury emissions make up 29% of total releases from both AGM sites. Most of the mercury used is lost in the mine wastes (71%), and potentially up to half of that may be carried by run-off with the suspended sediments. The resulting mercury contamination may negatively impact fluvial biota for many kilometres downstream of sites where waste discharges into streams.

Laboratory analysis confirmed the presence of mercury in every context in which it was expected, though concentrations are relatively low compared to artisanal mining communities in other countries in Asia and South America. This reflects the fact that local miners do not burn amalgam indoors, nor use mercury in excessive amounts of the gold they can recover. Artisanal mining in eastern Congo creates a vast, dispersed, low grade web of mercury contamination and methylation hot spots. This can impact the long term health of ecosystems and people across broad swathes of poor, rural areas. In addition, arsenic concentrations 10 to 20 fold above recommended standards were detected downstream of the Butuzi mining sites, which can cause serious health problems.

Table 1: Average values for mercury inventory measurements in Butuzi and Some.

Inventory measurement	Average N=11	Standard deviation
Mercury applied	4.09 g	3.98
Amalgam	0.50 g	0.42
Recovered Mercury	3.62 g	3.73
Gold sponge	0.23 g	0.19
Mercury lost	1.00 g	1.14
Mercury:Gold	4.3:1	2.74
% lost to air	29	0.10
% lost to land	71	0.10

A positive finding is that some miners produce relatively modest and confined mercury releases by concentrating the gold in their ore using simple sluices before applying mercury. This relatively good practice, however, is typically offset by the large quantities of tailings and primary material processed using whole ore amalgamation (in which mercury is applied to all of the primary ore). Preliminary mercury inventories of the sites suggest that the ratio of mercury losses to gold produced lies in the range between 2:1 and 7:1 (averaging 4.5:1), which is consistent with assessments of other African artisanal mining sites with similar work practices. This ratio of mercury to gold use is high and inefficient by international standards but low in comparison with more mechanized practices in the Americas and Asia.

Action plan for reducing mercury emissions

Artisanal mining sites should be organized so that all mineral processing, mercury use and tailings storage occur 1km (or at least 500 m) away from all natural water sources, villages, markets, and restaurants. The site must be on high ground to prevent inundation and all drainage from the area must go through settling ponds to reduce suspended sediment emissions. The process of amalgamation of reprocessed tailings must be replaced by better primary processing of ore so that all recoverable gold that can be concentrated or amalgamated is extracted in the first pass. Further recommendations for testing include using a blue bowl gold concentrator to process tailings and recover mercury and gold, and varying the sluice water flow rate, among others.

Mercury use can be greatly reduced or eliminated completely by changing how the ore is processed. The strategy should be to prioritize increasing pre-concentration before amalgamating. Efficient pre-concentration incurs gold losses, so processing in all parts of the chain needs to be improved, from exploration and planning of deposit extraction and mine workings, choice and pre-processing of ore, efficient grinding for gold liberation, as well as concentration and monitoring of gold in ore and waste. Overall, higher gold recovery can be achieved without mercury. Technology and training are the solution, assuming not only formality but access to investment and services.

A progressive plan of action to reduce mercury use and pollution is proposed below. The plan starts with changes requiring the least investment and training, followed by progressively costlier and more complex changes that can be added when the miners are ready to take the next step[2]. Consultations with miners and local communities will need to be organized to obtain their views and buy-in on the proposed plan.

Immediate action:

1. Promote use of retorts or fume hoods to recover mercury and reduce exposure and inhalation of toxic mercury vapours. Miners must stop using leaves as a retort.
2. Promote concentration and direct smelting as an alternative to whole ore amalgamation.
3. Improve water supply and waste management using impermeable reservoirs, refilling old mine pits, and reorganization of processing activities. This will isolate mercury releases and reduce infiltration of water into landslide initiation zones.

Medium term objectives:

4. Analyze gold ore mineralogy to guide changes in processing methods for both milling and gravity concentration.
5. Optimize mill feed, speed, duration, and grain size control, also using participatory controlled trials (including installation and comparison of existing milling equipment).
6. Improve existing sluice practices by optimizing flow velocity, feed consistency and turbulence through participative, controlled trials on site.

[2] Detailed information and guidance on the solutions outlined below is given in the following UNEP document: *Reducing Mercury Use in Artisanal and Small-Scale Gold Mining: A Practical Guide*

7. Field test different mechanical concentration devices on site, beginning with shaker tables, spirals, blue bowls, and jigs, using short term trials of lab scale equipment (which can also be used to further upgrade primary concentrates to enable direct smelting).

Long term goals:

8. Implement best practice wet milling and concentration processes. Potential options include using the Artisanal Gold Council Burkina Faso micro scale processing plant as a model[3].
9. Use trenching and panning (basic) and potentially also modern geophysical instrumentation (such as electromagnetic surveys or other) to study gold reserves and plan mining activities.

The above plan will improve gold recovery while progressively reducing, and eventually eliminating, mercury use. It applies equally to hard rock and alluvial mining sites.

Other environmental issues

In addition to mercury contamination, other major environmental impacts at the two AGM sites are deforestation (Some/Kafiawema area), increased risk of landslides (Butuzi), and fluvial degradation. In addressing these challenges, a systems approach may be adopted to capitalize on supplementary benefits that could be derived by linking transparency, land use planning, and pollution control, where feasible. For example, sustainable forest management and timber transparency initiatives would be a natural corollary activity, with benefits to communities and local ecosystems that come from land use planning and technological transformation.

Land use planning in the context of gold production requires basic exploration and ore body estimation in order to tightly constrain the excavations and site tailings disposal and camp locations with minimal impact and maximum regenerative potential. Combined mine and forest planning should be directed toward offsetting social and financial risks of formalization and new production technologies. Addressing these problems in isolation would ultimately overlook important unanticipated consequences and miss potential leverage points. For example, it would not be wise or sustainable to solely focus on diverting gold wealth from armed groups without consideration of the rapid irremediable devastation to large patches of contiguous Central African equatorial rainforest. Neither is it possible to ignore the possible deaths and injuries of hundreds of people in landslides and catastrophic flooding induced by uncontrolled mountain slope destabilization from artisanal mining. These threats risk reputational damage to PAC's pioneering pilot project and may undermine its impact. It is therefore important to establish a risk mitigation plan demonstrating proactive mitigation actions will be taken. In the Butuzi case, a number of simple measures are recommended that could diminish slope destabilization and exposure of people to the hazard area, but the threat will remain.

[3] See *AGC Burkina Faso Update report* and video film *Emploie l'Or Artisanal pour l'Aide au Développement.*

1. Introduction

This report is an environmental assessment of mercury pollution in two artisanal gold mining (AGM) sites in the eastern Democratic Republic of the Congo (DRC). It was conducted by the United Nations Environment Programme (UNEP) based on fieldwork in Butuzi, South Kivu (11-15 March 2016) and Some, Ituri (18-22 March 2016). The specific purpose of this assessment is to provide technical advice and support to Partnership Africa Canada[4] (PAC) in the implementation of its pioneering 'Just Gold' project, which aims to bring legal, conflict-free, and traceable gold from the two aforementioned artisanal mine sites to international markets.

The primary focus of this study is on assessing mercury use and releases into the environment and the identification of contaminated hot spots. For this purpose a rapid mercury inventory in the two AGM sites was carried out based on guidance developed by the UNEP Global Mercury Partnership for the Minamata Convention on Mercury; namely the Minamata Initial Assessment (MIA) and National Action Plan on Artisanal and Small Scale Gold Mining (NAP). Environmental samples (soil/sediment and dust) were collected and shipped to Spiez Laboratory in Switzerland for analysis. In addition, the report addresses other environmental problems and associated health and occupational risks at the two aforementioned AGM sites, as well as some of the broader governance challenges facing the artisanal gold mining sector.

In addressing the multiple environmental challenges at the two AGM sites, a progressive strategy taking into account investment costs and the complexity of measures is proposed. It is comprised of targeted technical interventions to:

i) reduce mercury use and pollution;
ii) help mitigate slope destabilization, deforestation and biodiversity loss; and
iii) improve occupational safety in the mining sites.

Furthermore, it is important to emphasize that reducing and eliminating mercury use is not only a health and environmental protection measure. As technological improvements for mercury reduction leads to increased gold yields, it is also an integral component of the incentive-based model that the Just Gold project aims to develop to encourage artisanal producers to sell their gold through legal channels. Awareness raising including practical demonstration trials is equally critical for promoting mercury reduction measures and their adoption by artisanal miners.

The technical assistance provided in this report is part of a collaboration between PAC, the UN peacekeeping mission in the DRC, MONUSCO, and UNEP to support the formalization of the artisanal gold mining sector by helping control the extraction and trade in gold.

[4] Partnership Africa Canada is focused on developing innovative approaches to strengthen natural resource governance in conflict-affected and high risk areas. PAC is an official partner organization of the International Conference of the Great Lakes Region (ICGLR), and receives funding from a broad range of governments and institutions to address the issue conflict minerals in the Great Lakes region of Africa.

Artisanal gold mining

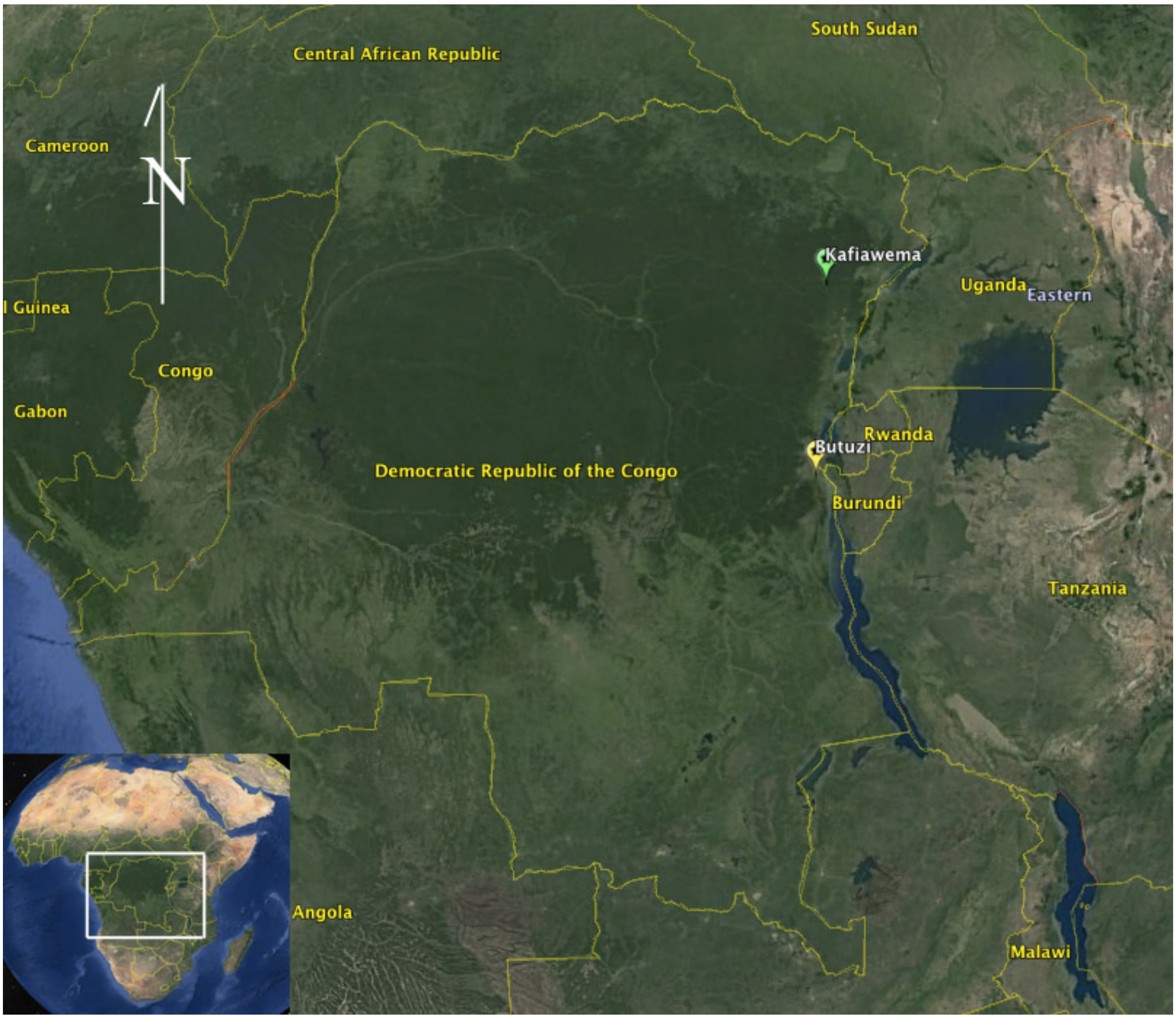
Photo 1*: An amalgam of gold and mercury before burning*

Artisanal miners use rudimentary methods to extract minerals due to lack of access to appropriate equipment and resources, caused by poverty and tenure insecurity. Mining refers to the extraction of the gold bearing material ("ore") from the ground, which is the most dangerous and laborious part of a mining operation. Mineral processing separates gold from the ore. In hard rock (ore "lode") mining, one first has to crush and grind the rocks to liberate the gold. Alluvial miners usually only excavate the ore and separate the gold as it occurs mostly as free nuggets and dust. Both alluvial and lode gold miners concentrate their ore to make separation feasible. With the right equipment it is often possible to extract the majority of the liberated gold using a combination of different concentration tools that progressively upgrade the concentrate and capture gold losses.

Chemical separation using mercury or cyanide is often applied to gold concentrates to extract the portion of the gold that inevitably cannot be extracted using concentration methods alone. Mercury picks up gold particles as it mixes and filters through the grains of ore, forming an "amalgam" of roughly equal parts mercury and gold. The amalgam can then be evaporated to leave only the gold behind. Mercury is easily recovered by panning, though significant amounts of mercury will always adhere to the ore. These contaminated wastes (or "tailings") must be disposed of durably and isolated from bodies of water. Metallic mercury used by miners is insoluble. Under certain conditions, however, elemental mercury can be transformed into more toxic methyl-mercury species that can disperse more easily and bioaccumulate in the food chain. Mercury in the food supply (especially fish) is the main mechanism of human exposure to mercury for people not directly involved in mining. Translucent tea coloured water, typical of tropical environments, is rich in organic compounds and likely has oxidation-reduction potential (Eh) and pH conditions that are favourable for methylating mercury. Mining effluents also tend to contain fine suspended sediments. The nanostructure of suspended clays consist of stacks of atom thick sheets that provide many excellent binding sites for mercury, and may catalyze transformation into reactive species that are precursors in the methylation process.

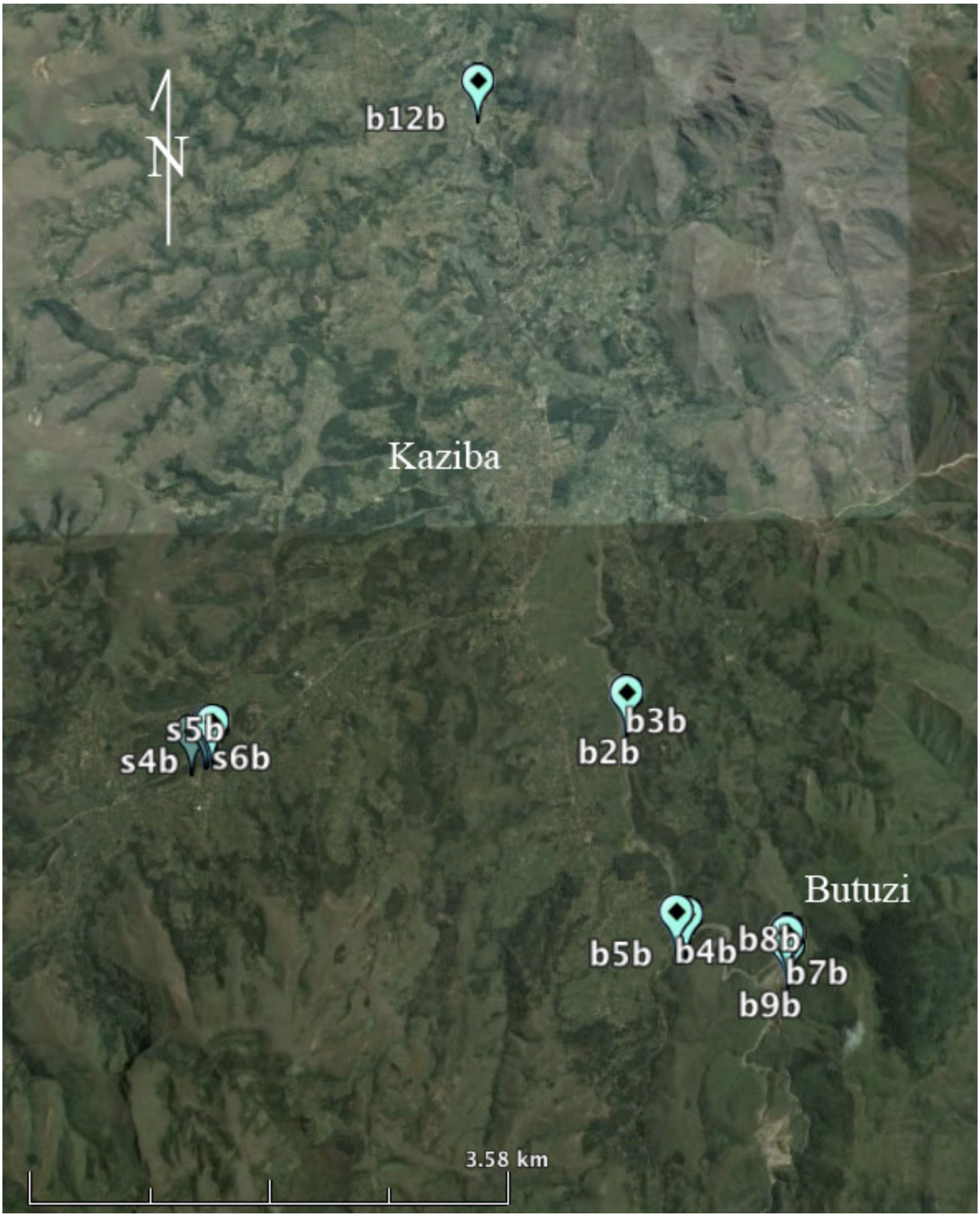
Many artisanal miners are not sufficiently aware or adept at gold concentration, and instead apply mercury to all of their ore, for example by adding it to grinding or concentration devices. This is known as whole ore amalgamation, and it is perhaps the most important of the worst practices identified by the Minamata Convention on Mercury. Miners who concentrate gold in a sluice usually emit half of the mercury compared with those who practice whole ore amalgamation, because much less material comes into contact with mercury. Promoting more efficient mining practices can help motivate such behavioural changes, as they produce more gold while using less mercury or none at all.

Mercury recycling is another important behaviour change that can reduce emissions and costs. Small mercury distillation devices called "retorts" condense mercury vapours that are emitted when the amalgam is burned, and larger condensers can be built to trap mercury emissions in advanced refining steps.

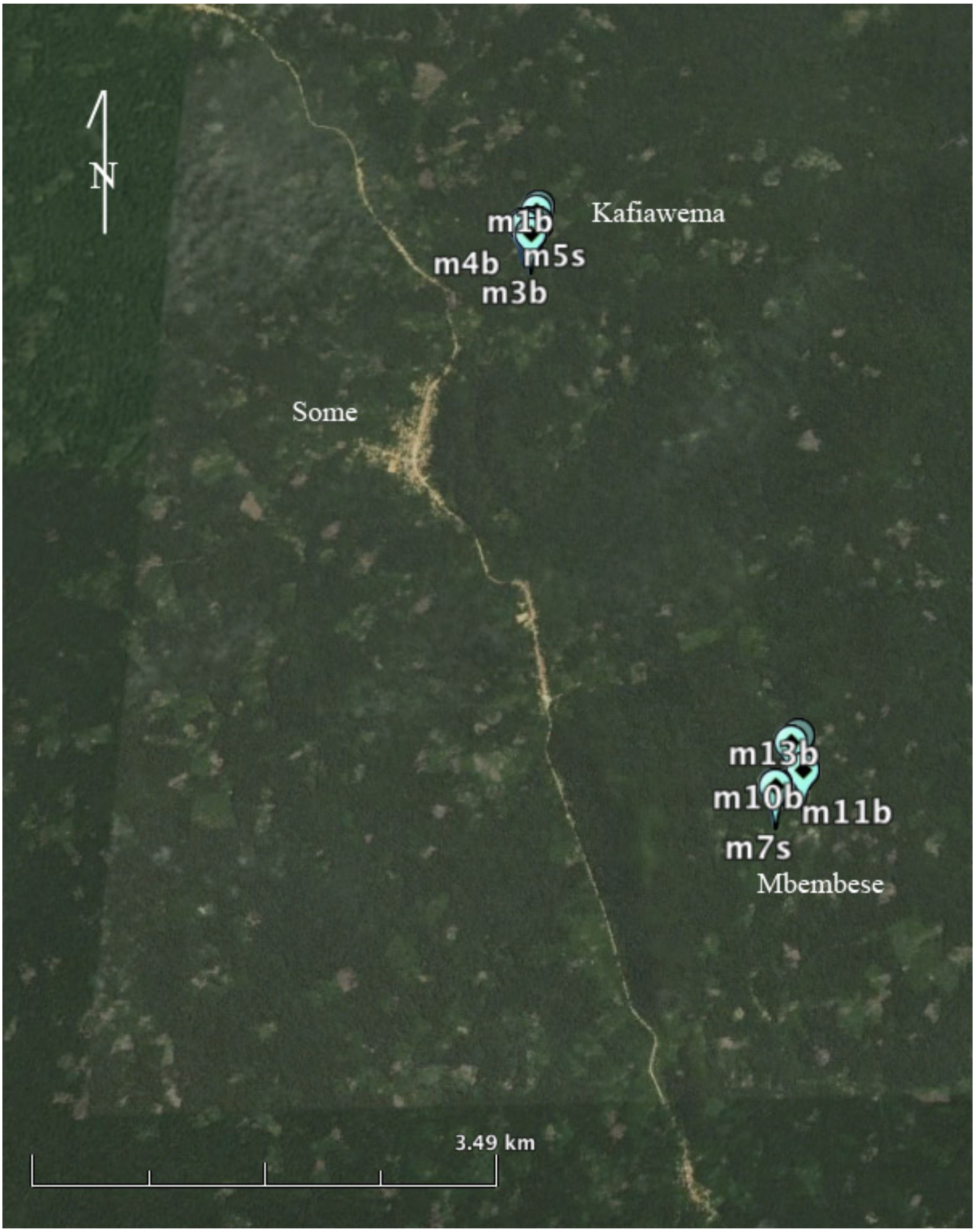


***Map 1:** Map of the Democratic Republic of Congo, showing the main field sites. Google Earth imagery*

Map 2: *Spatial context of Butuzi mine site and its location vis-à-vis the main population centre of Kaziba village. Google Earth imagery*



Map 3: *Overview of Kaziba/Butuzi area (South Kivu); sampling locations and codes are explained in the methodology and results (Appendix 1). Google Earth imagery*



Map 4: *Some/Kafiawema (Ituri) area showing deforestation patches; sampling locations and codes are explained in the methodology and results (Appendix 1). Google Earth imagery*

Gold mining in eastern DRC

Artisanal gold mining has been waxing and waning in eastern DRC over the past century. The two artisanal gold mines examined here have only been operational for 10 to 15 years or less, which reflects the unpredictable, migratory nature of artisanal mining in this region. In terms of environmental impacts, these cases stand out not only for their mercury emissions but equally for the landscape disturbance and forest degradation they produce. Nevertheless, it is important to reduce mercury at these sites to provide a test case for the elimination of mercury use, as the cumulative emissions of hundreds of such operations across the DRC amounts to a serious contamination problem. Understanding the nature of these operations is key to modifying activities for the reduction of environmental and human health risks.

Butuzi AGM site, South Kivu

The Butuzi site lies in a rugged highland terrain in the Mitumba Mountain range along the western edge of the Albertine Rift Valley. Naturally dominated by Afro-montane forest, the region has been almost completely deforested for many decades. Administratively, the Butuzi site is located in Kaziba Chefferie (Walungu Territory, South Kivu Province), which has an estimated population of around 45,000. Travelling the ~55 Km dirt road from the provincial capital Bukavu to Butuzi takes around three hours by four-wheel drive vehicle.

Photo 2: *View of Kaziba village from the hills near Butuzi AGM site*

The main economic activity in Kaziba Chefferie is subsistence agriculture (cassava, maize, potatoes, beans) and traditional livestock rearing. In the past, cash cropping (coffee, quinquina) was practiced but appears to be largely neglected. Woodland plantations (cypress, pine, eucalyptus) are extensively grown for the production of poles and planks. A major supply center for Bukavu, wood production reportedly provides the main source of cash income for the local population.

South Kivu Province

Surface Area: 69,130 km^2
Population (2005 estimate): 3.9 million
Provincial Capital: Bukavu
Population density: 60 persons/ km^2
Agriculture: 70% of provincial GDP
Artisanal miners: >100,000 (85% in gold mining)

Source: *MONUSCO (2015), Stratégie Provincial de Stabilisation et Plan d'Action pour la Province de Sud Kivu; PNUD (2009) Province du Sud Kivu : Profil Résumé Pauvreté et Conditions de Vie; IPIS (2014): Analysis of the interactive map of artisanal mining areas in Eastern DR Congo*

Butuzi artisanal mining

Artisanal mining takes place on the steeper mountain slopes that are too difficult to cultivate. In the Butuzi site, mining is taking place along the face of a very steep mountain slope (>30° with a fall of ~200 meters) that runs down into the Luzinizi river valley. The crest of the Butuzi hill reaches an altitude of around 2,200 meters dropping to around 2,000 in the Luzinzi River below. Miners that live in Kaziba hike up to the Butuzi mine site in under one hour.

Entering the Butuzi site, one can see the uncontrolled destabilization of the slopes up close as well as in the middle distance and successive ridges in the background. All have created a massive, imminent landslide hazard by removing anchoring vegetation, and digging unlined reservoirs as a water supply. Water is manually pumped into hand dug open channels and/or hoses using wash basins, and this feeds the earthwork 'sluices' burrowed on the mine face. Water percolating into joints, fractures and the slide plane through the water collection pits and haphazardly constructed water ditches will further weaken the slope over time. Cracks are evident in adjacent slopes, suggesting that active landslide initiation zones are under tension and ready to collapse. Miners send bulk dirt (either barren or amalgamated tailings) as well as large boulders tumbling down the slope, which creates waste slides that undermine slope stability in a long line down to the river. The mines themselves create another stability problem, as unmapped mine tunnel passages risk both eroding the slope from within and by cave-ins from unexpected intersection of workings. Not all mine entrances are buttressed as in photo 4, and the inside is sparsely reinforced, if at all.

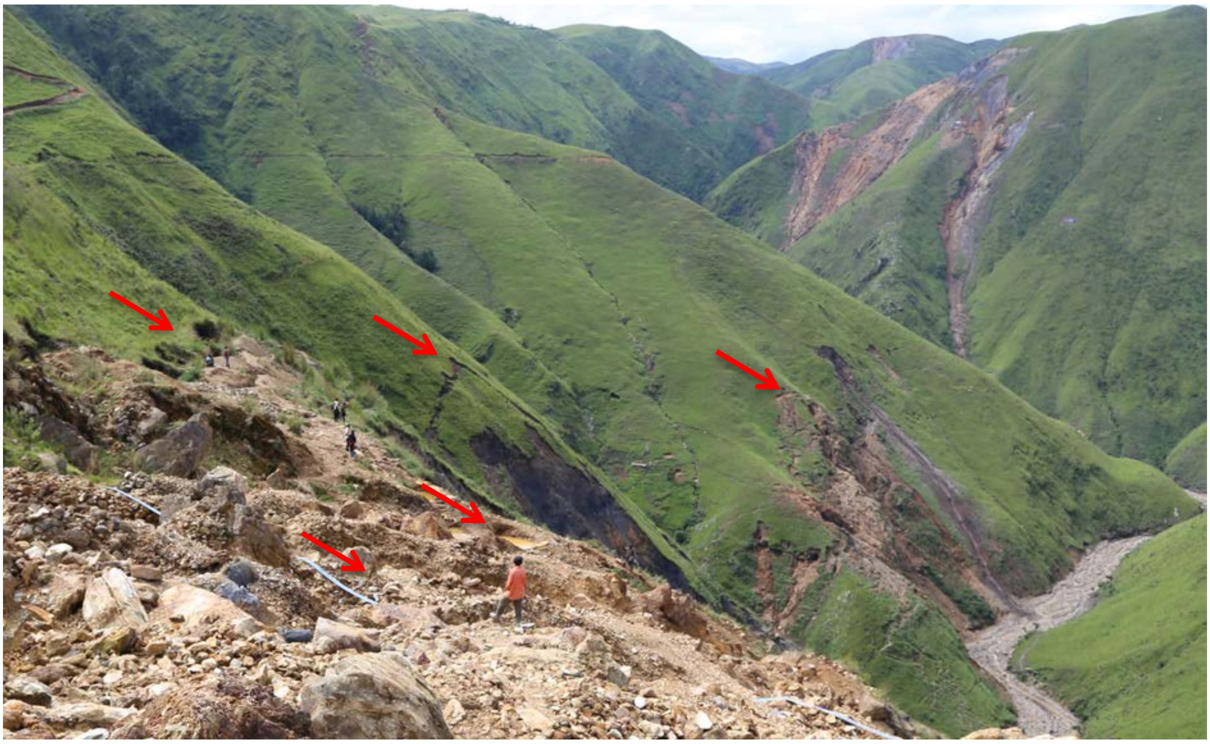


Photo 3: *Butuzi mine entrance. Note the grass fringed rain collection pits visible in the far left of the photo, at the top margin of the disturbance, and the hose that brings water by gravity to the sluices below. Above the person in red are three amalgamation ponds full of yellow mud. Grey and red waste chutes are visible right of centre, and landslide cracks left of centre. The river below is full of alluvial miners every day, all year*

Photos 4 and 5: *Rudimentary mine entrances and tunnels are sometimes buttressed by wooden beams, but these supports are few and tunnels are prone to collapse. Miners pan ore in shovels to test the gold content of ore*

Photo 6: *Imprecise weights used in local gold markets appear to favour the buyers*

The Butuzi miners are exploiting primary rock deposits, but only work the unconsolidated near surface saprolite deposits where the gold has already been liberated and concentrated by chemical weathering. This suggests that a large amount, perhaps the majority, of the gold in their deposit is contained in the hard quartz rich blocks of rock that they send rolling down the hill as they dig for gold bearing sand. Miners search out the yellow and red sands in between harder blocks of rocks, making circuitous tunnels as they chase the high grade sands deeper into the mountain. This search is directed by periodic artisanal "assays[5]" in which miners pan a sample of the ore in a shovel to see if they can see particles of gold inside. This "assay" is also used to determine how much mercury is to be applied.

Butuzi miners that sluice tend to work in larger teams that coordinate the digging, sluice construction, water management, and concentration amalgamation roles. It is important to study and understand these existing organizational structures so that they can be adapted and expanded to include new roles demanded by the implementation of best practices. As a group, sluicing miners pay about 10 US dollars per day for daily water costs (~5000 FC for water and 4000 FC for pipe rental).

Butuzi miners typically work 6 days per week all year long for an average daily gold production of 0.5-1 grams. They are paid between 34-37 US dollars per gram. However, the methods of weight measuring are imprecise and from spot check visits to the local gold market appear to favour the buyer. That is, if the buyer weighs the gold as 1 gram, it in fact may weigh more than that, which is one reason why buyers can afford to apparently give near market price for the deflated weights determined by them.

[5] In mining, an assay refers to a physical analysis of an ore, metal or alloy.

Photo 7: *Note the web of cracks in the copper mine on the adjacent slope, and the grey waste rock dump slide stretching half way across the riverbed. Sinuous patterns created by walled channels built by the alluvial miners can also be made out below*

The Luzinzi riverbed below this mine site is completely altered by the accumulation of mine waste, induced landslides and the action of hundreds of miners that work along the river daily. The miners are constantly exposed to the landslide hazard above.

They also restructure the riverbed to create sluices, basins, and cobble walls that protect manufactured channels and hold back waste sand that they have already worked. These sands are repeatedly reworked over time because their methods are so inefficient that there is always more gold to extract in any mine waste. Periodic floods probably also help to mobilize and concentrate the gold.

Butuzi mineral processing

Butuzi miners do not crush or grind their ore, instead concentrating free gold found in loose sands inside their tunnels. Some use sluice channels dug out of the slope and lined with banana bark. Sometimes they also put mercury in the banana bark, which inevitably leads to losses. Individual miners tend not to use sluices, and instead pan concentrate their ore by hand. They mix in mercury into the whole ore using plastic wash basins in small amalgamation ponds. Each miner puts one ~50kg rice sack of ore into the plastic basin, as well as several grams of mercury, depending on the richness of the ore. The amalgamation ponds are unlined and not sufficiently contained to prevent groundwater infiltration or overflow emissions of mercury bearing suspended sediments during heavy rains or inundation.

Photo 8: *Wall and channel structure of heavily worked river bed*

Waste discharges from hard rock mining in creeks and rivers, as well as the disturbance of alluvial miners working in the larger rivers, completely alter the fluvial morphology of areas they work. Siltation destroys fluvial ecosystems, rendering formerly fish bearing rivers barren and eliminating an important source of local protein.

Mercury use is usually controlled by the head of an artisanal mining team (so-called PDG, President Directeur-General, i.e. CEO), who apportions inputs free of cost according to the potential gold content in the ore as assessed using their artisanal "assay" method of panning a sample of the ore in a small gold pan. The PDG is usually very conservative in his application of mercury, in contrast to operations in Asia and Latin America which generally apply mercury far in excess of what is optimal, with the false expectation that this will ensure maximum possible recovery. Miners then thoroughly mix the mercury in with the ore or concentrate using bare hands in a plastic wash basin. After mixing, the ore is panned to gradually reduce the mass of ore in the basin until almost all is discharged and they can easily recover the liquid mercury. This mercury is then squeezed through a cloth, taking care to catch the excess mercury in the wash basin. That mercury is returned to the PDG. Next, the resulting amalgam is burned over a charcoal fire. In Butuzi the mercury is dispensed from an eye dropper, and in Some they use small syringes. Most mercury is lost to the tailings, though the most immediate public health risk results from open amalgam burning.

Photo 9: *Open air burning of gold amalgam with a tablespoon on charcoal stove*

Photos 10 and 11: *Banana bark makes an effective, if inefficient, gold concentrator (left). Proper carpets and a smooth, 10 sloped sluice bed would be more effective in capturing gold. Plastic wash basins make relatively poor gold concentrators, and proper gold pans would be more effective*

Photo 12: *Mercury droplets visible on the banana bark*

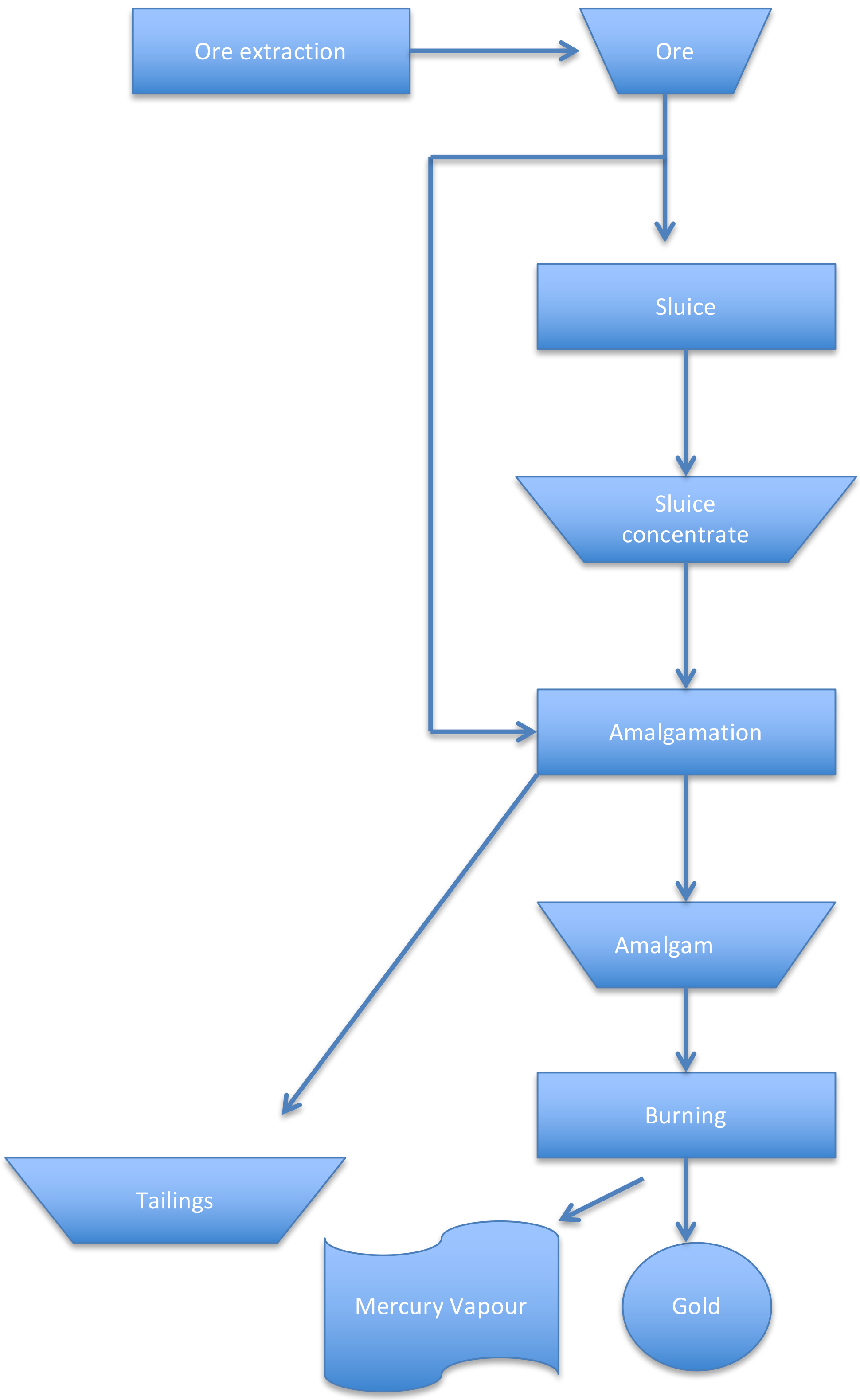


Diagram 1: *Flow diagram for mineral processing in Butuzi. Sluices are only used by groups of miners. Independent miners use whole ore amalgamation each time they extract one sack of ore.*

Photos 13 and 14: *The PDG manages the mercury for the site, which is handed out for free to miners, and then collected in the same bottle or syringe after the excess is squeezed out of the amalgam*

On the Luzinzi river, below Butuzi and adjacent to Kaziba, sluices are dug into the riverbed and lined with large rocks on the sides and banana bark as a concentration medium. Miners scoop sands and gravels into shovels and wash them by dipping them into the water current at the top of the sluice and throwing them into the air and catching them again several times in succession. This separates the fine sediments that contain the sought after gold dust that is concentrated as they flow down the sluice. The washed gravels are tossed into waste piles.

Photo 15: *Repeated reworking of sands right at the edge of the village agricultural fields*

Some AGM site, Ituri

Some is located in Ituri province, in a flat equatorial rainforest (<900 meters) which is still relatively intact but under increasing deforestation pressure. The AGM site is adjacent to one of the DRC's most important protected areas, the Okapi Wildlife Reserve (OWR), which is also a UNESCO World Heritage Site that is on its 'Danger List' since 1997. Situated within a 25-30 kilometre distance from the ORW, Some falls within the designated 50-km buffer zone surrounding the entire Reserve.

Miners in the Some area of Ituri province practice a mix of alluvial and hard rock mining, though apparently only the hard rock miners use mercury. There is a distinct possibility that alluvial miners will realize that mercury can also improve alluvial gold production. Therefore, it is important to monitor alluvial operations and provide them with more productive methods so that they have good alternatives to mercury. Alluvial miners and hard rock miners leave large holes in the forest unfilled and barren of good soil. This creates a pockmarked landscape of stagnant ponds, gravelly soils, and disturbed water courses.

Kafiawema, the main Some area mine site investigated in this study, is located 30 minutes south of Mambasa, mostly on good dirt roads. Although there is a miner's camp located at the mine site, many miners live in nearby Some, which is about 30 minutes away on foot. Most of Some's ~400 inhabitants are directly involved in mining, although logging of high value hardwoods (often illegally), and some agriculture (mostly subsistence) are also practiced.

Ituri Province

Surface Area: 65,658 km^2
Population (2005 estimate): 4.2 million
Population density: 65 persons/km^2
Provincial Capital: Bunia
Artisanal mining : almost entirely gold
Artisanal production: ~2 tonnes

Source: *Site Officiel de la Province de l'Ituri (2016): http://provinceituri.info/; IPIS (2014): Analysis of the interactive map of artisanal mining areas in Eastern DR Congo*

Kafiawema artisanal mining

The ore bodies used by the Kafiawema miners consist of thick, hard, and contiguous quartz veins. This material is broken apart, hauled out, and crushed to “millable” chunks, all by hand.

In Kafiawema, the family of the present concession holder discovered a gold bearing vein behind their house, so the entire camp is being moved to allow exploitation of the new vein. Apparently that person now has legal provincial title to mine aggregate (stones, gravels, sand) at the site. Seemingly, provincial authorities are using quarrying licenses to also cover gold mines (whose mandate normally lies with the central government). Moving their camp to expand their mining operation, means clear-cutting another patch of climax equatorial rainforest.

Photo 16: *Open pit mines can only operate as long as the water is pumped out and pit walls are stabilized. This imposes limits on the depth of exploitation, and expands the area that must be cleared to sustain the same number of miners over time. Pits are dug with hand tools and water is removed with gas powered pumps*

Kafiawema mineral processing

The miners of Kafiawema use a dry mill with steel balls. The mill and balls are visibly worn down. There is no control over the mill speed, though they control the size of mill output by using a ~1mm sieve. This is a roughly appropriate discriminating size for most primary concentration applications. Nevertheless, the precise control size can only be assessed by formal granulometric analysis.

This is a relatively simple analysis that would normally be conducted during the baseline and planning stage of a project. Instead of returning oversize material to the mill for further grinding, miners instead hand it over to the manual stamp millers. These millers use a metal variant of the traditional mortar and pestle method for hand pounding manioc root flour.

In Kafiawema, the dry mill discharge is mixed with water to create a slurry that is fed to a sluice through a wash basin with 1-2 cm holes cut into the bottom. This creates a somewhat controlled flow of material onto the sluice. Fortunately, they do not first impregnate the carpets with mercury, so this first step is not whole ore amalgamation.

Photo 17: *This old diesel motor must regularly be fed fresh oil to keep it running. The capacity of miners to improvise this rough but functional mill drive system, demonstrates their capacity to learn to operate best practices equipment*

Next, the resulting amalgam is burned over a charcoal fire with green leaves covering the amalgam to trap some of the evaporated mercury. Most of the mercury is lost, but the small portion caught on the leaves is washed into the wash basin and more mercury is added to absorb the recovered mercury more easily. Suboptimal concentration techniques likely result in very low gold recoveries. This conclusion is supported by the fact that they can productively rework tailings multiple times (while also, of course, serially reapplying mercury). Miners have no other way to assess their productivity per unit ore because they do not study the bulk content of primary material (also known as the 'head grade').

The assessment team was unable to observe the gold production from sluice concentration of the ore that is ground in the ball mill in Kafiawema, nor inventory the mercury used in the amalgamation of the sluice concentrate of that material. This is unfortunate, as it is undoubtedly where most of the gold is produced, yet the expected amounts were not being sold at the PAC project's legal gold buying shop[6]. There seemed to be mistrust and a mistaken suspicion that the real purpose of this project was to buy the gold and profit from export. That opinion was expressed explicitly by miners at the community consultation in Butuzi, and project staff indicated this was a perception sometimes found in Some also. On one occasion when the sluice was not being used, it was observed that it was lined with a more optimal synthetic sluice carpet for concentration of the primary ore, instead of the towels and woollen mats used by others. When asked about it, the PDG said that they got those carpets from a formal mine nearby. It would be very useful to investigate this as a possible source of better sluice carpets locally, or potentially a local distributor.

The "owner" of the ore (in Kafiawema, this is the person that discovered the quartz vein) keeps the tailings as payment for the right to mine and also for distributing mercury to the miners for free. The mining tails of all the aforementioned processes are reprocessed 6 or more times using more mercury each time. All the miners are required to sell their gold to the PDG, who probably also collects a fraction of it as royalties for the "owner."

Photo 18: *Continuous reprocessing of mine tailings. Note the lack of organized tailings storage, or effluent control*

[6] PAC's Just Gold Model Trading House (*Maison d'achat modèle*) acts as the legal conduit for artisanally produced gold by purchasing it at competitive prices, packaging it, and selling gold to a partnered legal exporter (*comptoir*).

Photos 19 and 20: *This (left) is probably an appropriate mesh size for the Kafiawema ore (approximately 1 mm), at least for the primary grind. Granulometric analyses would better indicate the optimal size. Mortar and pestle secondary milling (right)*

Photo 21: *In Kafiawema the slope of this sluice could be optimized, and the two sluice sections should be arranged in L or Z configuration to force the flow to stop and restart (most gold is caught in the first metre of the sluice, making a turn gives more effective sluice length*

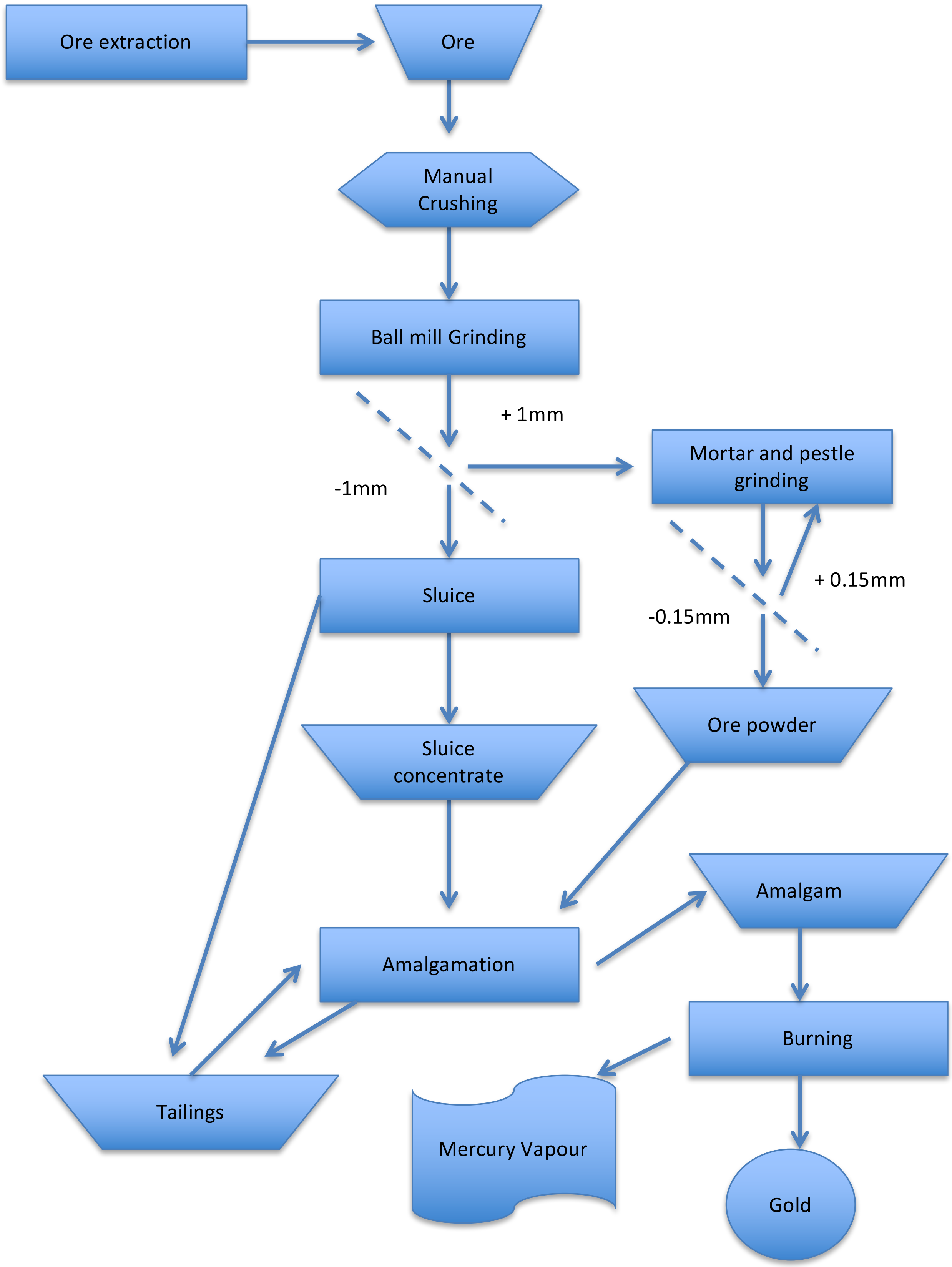


Diagram 2: *Flow diagram for mineral processing in Kafiawema. Sieves (symbolized by dashed diagonal lines) are used to control the size of material that passes to the sluice and manual grinding. Tailings are often reprocessed 5 times or more to extract further gold.*

2. Mercury assessment methods

Evaluation of the amounts and impacts of mercury contamination was through site investigations, community meetings, and environmental sampling (sediments and dust). Site investigations included direct measurement of mercury usage and recovery in each stage of mineral processing, which provides an estimate of the mercury emissions to air and land/water for each gram of gold recovered at the site.

The assessment methodology included:

i) discussions and interviews with artisanal 'mining cooperatives' and miners, gold traders, mining technical administration and local authorities concerning priority environmental and occupational safety challenges;
ii) site walkover survey to scope environmental problems;
iii) inventory quantifying mercury inputs and releases, and estimate the ratio of mercury losses to gold produced;
iv) collection of soil/sediment and dust samples. In total 57 samples were collected from both sites comprising of 29 soil/sediment samples; 26 swab samples and 2 geological samples. All samples were shipped to Spiez Laboratory in Switzerland for analysis.

In addition in both Butuzi and Some, consultation meetings were organized with artisanal mining cooperatives, miners, gold traders, the Mining Ministry and local authorities explaining the purpose of UNEP's environmental assessment, initial findings from the field visits and potential recommendations for progressive remedial solutions. These meetings also provided an opportunity to raise awareness and share information materials about the health and environmental risks of mercury use in AGM.

Sediment sampling

Sampling followed as closely as possible the Protocols for Environmental and Health Assessment of Mercury Released by Artisanal and Small-Scale Gold Miners (Veiga and Baker 2004). In general, samples were collected from least to most contaminated but it was not always feasible to successfully define those zones. The disorderly arrangement of operations, legacy mining impacts, and upstream operations make it difficult to find "pristine" control points. Sites were chosen for their potential to accumulate mercury. This included tranquil areas along river banks where fine sediments accumulate (e.g. on the inside of a meander), amalgamation ponds, and areas of deposition of mine tailings or sediments that had been sluiced and amalgamated.

Most samples were of river or amalgamation muds and sands collected from beneath standing water. Bottle samples were obtained by taking a composite sample of several trowels full of submerged creek bed sediment, mostly near the creek edges where water eddied out and dropped its fine load.

Photo 22: *Swab sampling on market stalls next to which open air amalgam burning takes place*

Each sample took sediment from 4-6 locations of the upper 10-20 cm of sediment, mixing in roughly equal amounts of deeper and surface sediment. Each sample was mixed in a plastic bag, and mixing bags were only used once, and the trowel was given away after each mine site visited to prevent field sampling contamination. Once visibly homogenized into a uniform colour, the mix was poured into the sampling jar, taking care to take some material from the top, middle, and dregs of the sample mixing bag. Each sample was labelled with the geographic coordinates, sampling time, sample number, description of the context in relation to the mine site, river or sediment characteristics and other aspects of the sampling site. The bottles were then sealed tightly and packaged in two plastic bags tightly closed by twisting and tying.

Dust sampling

Dust sampling was done wearing rubber gloves to avoid contamination during handling, and marked with geographic coordinates, sampling time, and a description of the site being sampled. Sampling focused on finding sites near amalgam burning locations such as in home residences including kitchens, gold buyer and surrounding markets stalls, food kiosks and trees near open burning spots. Dust collection sites were always taken from shady locations where solar exposure would not be able to evaporate the mercury (such as roof beams, under shelves, under eaves, or walls in permanent shade or artificial lighting).

Photo 23: *Sediment sampling from the amalgamation ponds*

Mercury inventory

The Butuzi site is a challenging place to do a mercury inventory. The miners are often using minute amounts of mercury (<1g) to recover tiny amounts of gold. The masses involved are near the effective detection limit of the electronic balance used, which is higher than the manufacturers stated precision of 0.01 grams due to difficulties in finding level ground and the effects of wind gusts (which produce pressures in the 0.02-5 g range). Turbulent wind eddies peak later in the day when miners are amalgamating their ore.

To counter this instability, a plastic bag filled with sand was pressed to the ground and the scale was then driven into the bag in a way that it was level. In the future, a small circular level should be used to make sure that the scale is evenly balanced. A clear plastic cover dome or a glass bowl should then be placed over the scale to block the wind while recording the mass.

The miners also all tend to amalgamate at around the same time, so following the amalgamation process of one miner often precludes finding that of others. To make matters more complicated, there is typically one man who supplies all of the miners with mercury, so that one cannot simply track the changing weight of the mercury bottle to measure the amount of mercury recovered. Once this man gives mercury to one miner he proceeds to give more to another, then to get the mercury recovered from yet another miner and perhaps to give more mercury to a third miner. This makes it difficult to track the recovered mercury. Furthermore, dust and dirt grains sometimes adhere to the tiny mercury droplet, which may add a relatively significant mass to the recovered mercury given how small the recovered mercury droplet can be.

Photo 24 and 25: *Mercury inventory using an electronic balance to measure ratio of mercury loss to gold produced*

As a result, it is sometimes necessary to use a piece of paper to hold the recovered mercury or amalgam. The miner, however, often wets or drops particles of ore or mud onto this paper when transferring the mercury to the paper. The solution to this is to tare the balance with the paper on it, and then to measure the empty paper afterward to see the change in mass due to contamination during mercury/amalgam transfer.

Unfortunately, a higher precision balance would have even higher requirements for levelling and is likely not practical in this kind of field setting. Also, mercury is used and stored under water, so it is important to separate the water before measuring the mercury. A soft plastic sponge can be pressed to the surface of the mercury, which will draw up the water but not mercury.

3. Analysis results

Mercury was found in every context in which it was expected, though concentrations are relatively low compared with artisanal mining communities in other countries. This reflects the fact that local miners do not burn amalgam indoors, nor use mercury far in excess of the amount of gold they can recover. Artisanal mining in eastern Congo creates a vast, dispersed, low grade web of mercury contamination and transformation hot spots. This can impact the long term health of ecosystems and people across broad swathes of poor, rural areas. Mercury vapour exposure is a more acute problem for miners themselves and those living and working near mining related mercury emissions in mining camps, villages, and cities. All values are measured in mg/kg (equivalent to ppm). Full analytical results are given in the appendices. Normal levels in soil range from 0.05 to 0.08 µg/g (Veiga et al. 2004). As the DRC has not established standards for mercury in soil and sediments, samples are evaluated against Canadian and Swiss guideline values.

Table 2: Soil and sediment quality guideline values in Canada and Switzerland (mg/kg)

	Canada		Switzerland	
	Mercury	Arsenic	Mercury	Arsenic
Soil	6.6	12	0.5	No value in legislation for soil protection
Freshwater sediment	0.17	5.9	0.5	No value in legislation for soil protection

***Map 5:** Kafiawema mine camp detail showing mercury sampling sites. Google Earth imagery*

Map 6: *Butuzi mercury sampling locations. Google Earth imagery*

Map 7 and 8: *Bukavu city centre, and Katudu market (Kaziba) sampling locations. Google Earth imagery*

Map 9: *Overview map of Mambasa/Kafiawema/Some area. Google Earth imagery*

Map 10: *Mbembese mercury sample location map, showing old unfilled alluvial mining pits on the right. Google Earth imagery*

Sediment analysis

Background soil concentrations (0.018 – 0.34 mg/kg) in the Kivu region are elevated but well below international standards. Sediments in the area of the Luzinzi river (0.064 – 0.091 mg/kg) where Butuzi and other miners discharge and hundreds of artisanal alluvial miners practice amalgamation, exceed guideline levels downstream of Kaziba town. Natural arsenic released by oxidation of sulphide minerals in mine tailings has increased substantially. Arsenic concentrations 10 or 20 fold above recommended standards in Luzinzi River sediments were detected, thus posing a potential risk to people downstream. The amalgamation ponds at the Butuzi mine site are rich in mercury up to 3.6 mg/kg) and arsenic (14000 mg/kg), which will periodically overflow and discharge down the slope into the Luzinzi.

Background concentrations of mercury in soil, sediment, and rock are low in the Some area and upstream of the Kafiawema camp (~0.1 mg/kg). Mercury levels are significantly enriched in waste dumps (up to 6 mg/kg) and sediments immediately downstream of mines (up to 5 mg/kg). Ore from Kafiawema contains significant amounts of arsenic (up to 310 mg/kg), which is liberated over time by oxidation in waste piles. Each mine site emits tailings and practices amalgamation in or near freshwater bodies that are slow or stagnant and rich in dissolved organic compounds, thus promoting the generation of reactive, mobile, and bioavailable mercury complexes.

Dust analysis

Swab sampling shows that mercury concentrations in Katudu market (near the town of Kaziba, where much of the Butuzi gold is sold) increase (from 0.2 to 1.7 mg/kg) as one approaches the gold buyers corner where amalgam is openly burned, despite the fact that miners burn their amalgam at the mine site first. Evidence of dust contamination from open air burning suggests that airborne mercury concentrations in the market are frequently far in excess of WHO health guidelines (1 microgram per cubic metre, WHO 2003), and is therefore a significant risk for people working and shopping there. Nearby stream sediment also contain mercury (0.3 mg/kg), though concentrations do not exceed guidelines. In Bukavu, swabs of walls near gold shop chimneys (1.2 – 7 mg/kg) indicate that sponge gold sold there contain significant amounts of mercury which could be putting thousands of urban residents at risk. Dust swabs taken in huts where mercury is stored or burned, and on trees near amalgam burn sites, were also found to contain significant mercury content (2 – 1200 mg/kg). In hopes of recovering mercury, miners place green leaves on top of the amalgam during burning, and a sample of these leaves contained more than 2% mercury by dry weight. Tens of grams of leaves as contaminated as this are produced and discarded haphazardly in and around mining sites on a daily basis across eastern DRC.

Mercury inventory

An adequate number (5) of mercury mass balances were undertaken at both sites to give a general idea of mercury use and release rates, and local PAC staff were trained to repeat them regularly. This will build up a longer term time series of mercury usage that offers a more reliable estimate of mercury releases and also track reductions due to changes in practices. On average, miners at both sites released more than 4 grams of mercury to the environment for each gram of gold they produced. One third of that mercury was emitted as vapour, and the rest is released to land and water.

Table 3: Butuzi mercury inventory (in grams)

	Butuzi						Average
Mercury applied	0.31	0.72	0.84			0.12	0.50
Amalgam	0.06	0.32	0.14	0.20	0.47	0.31	0.25
Recovered mercury	0.10	0.10	0.68				0.29
Gold sponge	0.03		0.08	0.11	0.25	0.05	0.10
Mercury lost	0.24	0.94	0.22	0.09	0.22	0.38	0.35
Mercury: Gold	8.00		2.75	0.82	0.88	7.60	4.01

Table 4: Some mercury inventory (in grams)

	Kafiawema				Some site 2	Average
Mercury applied	6.01	5.88	5.3	12.13	5.47	5.06
Amalgam	0.13	1.22	0.68	0.75	1.2	0.58
Recovered mercury	5.62	4.04	4.76	11.17	2.5	4.73
gold sponge	0.08	0.56	0.29	0.36	0.46	0.25
Mercury lost	0.44	2.5	0.93	1.35	3.71	1.11
Mercury: Gold	5.50	4.46	3.21	3.75	8.07	4.25

4. Mercury reduction

The following recommendations apply to both AGM sites. Mills[7] and retorts should be placed at least 500 metres downwind of habitation, food preparation, and all non-mining activities; and as far away as possible from natural bodies of water. The mill site should have a sluicing pond into which sluice tailings are collected, which drains into a series of sedimentation ponds that progressively remove fine sediments before discharging. A pond approximately ~5 m^2 in area should be sufficient, as tailings should be periodically dug out and reprocessed or stored.

The mill site should also have a long term tailings storage site that is higher than and at least 500 metres from water bodies, above the water table, dug out of iron rich clay soil. The location should also be marked with warning signs indicating the presence of mercury and toxic hazard. This excavation should be lined by iron rich (red) fine clay or a geomembrane to reduce percolation. Decommissioned mine pits can also be used for tailings storage. The mill site also needs a small concrete lined amalgamation pond, perhaps with low brick walls to increase the convenience of panning in it. Only the very last step of amalgamating the panned concentrate should be done in this pond, thus isolating all of the potential mercury releases.

There should be a proper retort and heat source on site, preferably a gas torch rather than the traditional charcoal method (the latter does not produce sufficient heat). Eventually there should be a sufficiently high temperature torch to directly smelt the gold directly instead of using mercury. The retort should be stored far from houses and restaurants, and never in or near peoples' houses. As the mill, tailings and amalgamation pond are all located right at the edge of the mine camp, the retort is currently kept right outside miners' residences which is dangerous practice.

Dust exposure reduction

The dry milling methods used at Kafiawema present a significant dust contamination problem that can produce short term and long term health problems. Therefore the mill should be relocated to a site far downwind of the mine camp. It would also be beneficial to determine typical prevailing winds for the area to ensure that the mercury and dust contamination is placed downwind from the village.

Improving mineral processing to eliminate mercury use

Eliminating mercury contamination and increasing gold production are compatible goals; in fact the latter is essential if miners are to make the switch to better practices. Mercury is the fastest, easiest, and most reliable means to separate gold from the ore. By contrast, gravity concentration is more time consuming, fastidious, and inevitably loses gold in direct proportion to the degree of concentration achieved. To make a high grade concentrate (grade is the concentration of gold in the concentrate) incurs greater gold losses than if one were satisfied with a lower grade concentrate. Therefore, it is important to reform the entire production chain to improve gold recovery by leveraging various inefficiencies that are a product of the rudimentary methods used by miners. Increasing gold production by closing efficiency leaks can offset the losses incurred by generating higher grade concentrates. This consists of improving milling efficiency (in the case of hard rock

[7]Note milling is not practiced at the Butuzi site, but this may be relevant in the future as mining activities advance.

mining) to ensure that gold particles are optimally liberated from the ore (mechanically broken away from quartz and other minerals) while not grinding these particles into shapes and sizes that are not amenable to gravity concentration. Furthermore, losses from gravity concentration can be reduced by optimizing methods according to the nature of the gold itself (size distributions and shapes of gold grains) and by designing a chain of concentration tools that upgrade concentrates sequentially and capture gold losses by recycling and upgrading tailings of earlier links in the chain.

This implies more complex systems should be laid out so as to flow concentrates and tailings into subsequent steps at the appropriate and consistent feed rates. Once established, these systems also require less labour, which can free miners to spend more time actually extracting ore from the ground. As a consequence it also establishes more technical tasks that must be managed by people with a higher degree of training, thereby diversifying the labour market within camps and encouraging participation in training and skills upgrading. This reformed mineral processing chain can be built link by link, beginning with the simplest methods requiring the least capital expenditure and training. Ideally, the gains in each step can help offset the cost of adding further links in the chain.

Analysis of gold concentrations in their primary ore should be a priority for this project, as it can show that gold is being lost and that alternatives are more efficient. It is important to note that precise determinations of efficiency are difficult to obtain except over many repeats through a long operational period. This averages out variability due to changes in ore grades and statistical difficulties such as the ‘nugget effect’ that plagues gold ores in particular. Nevertheless, initial mineralogical analyses can still provide sufficient evidence of potential efficiency gains to make and justify financial models of processing plants that suit a given ore.

In particular, the target milled grain size should be determined by laboratory analysis, and oversize materials screened out and reintroduced to the mill or milled in a secondary mill. This will produce the optimal gold liberation without over grinding. Instead of first grinding the oversize material enough to pass their primary (~1mm) sieve, Kafiawema miners grind the oversize material to a much finer mesh size (~<0.1mm; probably too fine). This results in gold losses due to the fact that the gold is hammered too flat for efficient sluice concentration and too fine for amalgamation. They use the same mortar and pestle stamp milling technique used to prepare food, and sieve the result with a very fine mesh to separate the coarse grains for further grinding. It would be best to mill all ore particles to ~1mm (or to the optimal size once this size has been determined), and then reprocess tailings of that process to a finer size once the gold has been removed. The over-milled material is also treated using whole ore amalgamation leading to maximum mercury contamination for minimum gains. Optimization should be done through a series of controlled experiments with large homogenous split ore samples that will enable miners/experimenters to directly compare gold recovery of different trials. There may also be ways to use the artisanal “assay” that artisanal miners are familiar with (in which they hand grind with a hammer and concentrate in a small pan to evaluate the gold content of the sample) as third party evaluation of the grade of resulting concentrates or mill output.

Miners do not currently use magnets to separate out the magnetic component of their concentrate, and sometimes grains of black sand could be observed adhering to their amalgam. Stirring a strong magnet covered in cloth around in the panning concentrate can eliminate a lot of the black sands, thus upgrading the concentrate and improving amalgamation. Furthermore, this is an important step in preparing the concentrate for direct smelting (melting the concentrate to separate the gold in the form of ingots).

In summary, mineral processing should be improved by the following actions in each step of the processing chain:

Crushing: strive for a uniform crush size so that milling proceeds uniformly. A mechanical crusher would free up labour for other activities.

Milling: Optimize mill speed, loading (including ratio of grinding medium, ore, and water), use a wet mill, replace worn out grinding medium (steel balls), and optimize grind time.

Concentration: Use proper sluice carpets instead of towels and blankets, use shaker tables, blue bowl concentrators, and panning to upgrade sluice concentrates to the point where they can be directly smelted.

Action plan for mercury reduction

Based on the above discussion on mercury reduction, a structured plan of action is proposed for the two AGM sites. The plan starts with changes requiring the least investment and training, followed by progressively costlier and more complex changes that can be added when the miners are ready to take the next step. Consultations with miners and local communities will need to be organized to obtain their views and buy-in on the proposed plan. (See also flow diagram for mineral processing of the two sites).

Immediate action:

1. Promote use of retorts or fume hoods to recover mercury and reduce exposure and inhalation of toxic mercury vapours. Miners must stop using leaves as a retort.
2. Promote concentration and direct smelting as an alternative to whole ore amalgamation.
3. Improve water supply and waste management using impermeable reservoirs, refilling old mine pits, and reorganization of processing activities. This will isolate mercury releases and reduce infiltration of water into landslide initiation zones.

Medium term objectives:

4. Analyze gold ore mineralogy to guide changes in processing methods for both milling and gravity concentration.
5. Optimize mill feed, speed, duration, and grain size control, also using participatory controlled trials (including installation and comparison of existing milling equipment).
6. Improve existing sluice practices by optimizing flow velocity, feed consistency and turbulence through participative, controlled trials on site.
7. Field test different mechanical concentration devices on site, beginning with shaker tables, spirals, blue bowls, and jigs, using short term trials of lab scale equipment (which can also be used to further upgrade primary concentrates to enable direct smelting).

Long term goals:

8. Implement best practice wet milling and concentration processes. Potential options include using the Artisanal Gold Council Burkina Faso micro scale processing plant as a model[8].

[8] See *AGC Burkina Faso Update report* and video film *Emploie l'Or Artisanal pour l'Aide au Développement.*

9. Use trenching and panning (basic) and potentially also modern geophysical instrumentation (such as electromagnetic surveys or other) to study gold reserves and plan mining activities.

Photo 26: *Sediment sample collection from the Luzinzi riverbed where alluvial mining is taking place*

5. Butuzi: Slope stabilization and risk mitigation

Slope stability is a complex problem and imminent threat. Large cracks are visible in adjacent slopes to the east of the main Butuzi site indicating that a large destructive landslide is inevitable. Slope failure will destroy several amalgamation ponds, mine entrances, and shacks below it, and endanger the lives of miners working in the river below. This will likely occur during a heavy and sustained period of rainfall, or after short bursts of concentrated rainfall; a high frequency event in Butuzi with a relatively low chance of triggering for any given event. The landslide may also be initiated by an earthquake; near certainty in the unpredictable and low frequency event of large earthquakes (magnitude 4 and above).

Map 11: *Massive slope failure induced by artisanal mining at the Butuzi site underscores the risk of a 'catastrophic' landslide damming the Luzinzi River and causing devastating downstream flooding. Google Earth imagery*

Miners tend already to avoid working the site in heavy rains and this should be encouraged and reinforced. In the event of a massive landslide, it could dam the river below, potentially to a significant height because the valley is steep sided and the river has only a narrow space in which to flow. The temporary dam thus created will build a large reservoir behind it, which may necessitate evacuation of low-lying areas along the Luzinzi River where a large portion of agriculture in Kaziba Chefferie takes place and where some people have built permanent homes. It may take months for the dam to breach, and the catastrophic outwash flood could kill hundreds and even thousands of people if they are not evacuated. A significant area of agricultural fields may be washed away or covered with debris, rendering cultivation impractical without significant efforts to remove it.

Photo 27: *Cracks visible in mountain slopes in the upper left and right of this picture are an alarming signal of imminent collapse*

Actual meaningful reinforcement of the mine site using conventional engineering structures is likely prohibitively costly with low probability of success. The rocks are shattered and altered both by tropical weathering and by the geothermal alteration processes that emplaced the gold in the first place. Inside the mining tunnels, the rock does not appear to become any more solid, but rather is poorly consolidated and deeply weathered. Not only does this present an extreme risk of tunnel collapse even without a seismic event, but also it means that the slope instability runs too deep and is too pervasive to use rock bolting or other heavy industrial techniques. In any case, it would be impractical to get the equipment for such engineering to this remote site.

Under these circumstances, disasters are inevitable. Indeed, a landslide last year was reported to have caused several deaths. In fact, injuries or deaths are likely simply from rockfall from miners operating above one another, as no one wears helmets and there is no mine planning. Apparently the miners are disposed to leaving some areas alone to decrease risks to other miners, or to work in rotating shifts. In practice this may be hard to agree on or enforce, but should nevertheless be pursued as part of mine planning.

Bioengineering techniques provide a relatively easy and low-cost option for slope stabilization. Vetiver grass (*Chrysopogon zizanioides*) is a good candidate for helping stabilize the steep slopes of the Butuzi mine site. Although classified as a grass, vetiver plants used for land stabilization purposes behave more like fast-growing trees or shrubs. Their extensive and finely structured root system can extend 2-3 meters in the first year reaching up to eight meters. While some of the exposed slope is bare rock or loose shale slopes, the rock layers are generally deeply weathered with many weak spots through which the vetiver's fast-growing and deep roots can penetrate. By planting the vetiver plants closely together at critical locations (e.g. along the top of the mine face and the footpath), dense hedges can be created to structurally reinforce the slope and also slow down and spread the water flow to help control erosion. Finally, it should be noted that there is good expertise in the DRC on vetiver use for slope stabilization and erosion control which can be utilized by the project.

Photo 28: *Water collection pits located above the Butuzi mine site increase infiltration into landslide initiation zones*

Controlling drainage is the other main method which can be used to mitigate slope instability and landslides at the mining site. Building a large concrete lined cistern and rain collection system on the hill above the mine site could provide the miners with a larger and more reliable source of clean water that would not impact stability and could be fed to the miners using gravity. Ideally, the cistern should be located on the east face of the Butuzi mine summit, at the elevation where the eastern approach trail descends into the mine site, but farther south so that if it fails it drains away from the mine site. Fixed tubes should connect the cistern to the top of the mine site where water managers can connect to a nozzle manifold to which they can connect their hoses. Hand-dug ditches to channel water to sluices should be stopped and replaced with large hoses.

Existing water pits should be filled in, perhaps with material dug out to create the new cistern, and planted with vetiver and ideally some trees also. If miners, however, are reluctant to stop using existing water pits, than these should be lined and reinforced with sand bags and terraces and planted with vetiver. In either case, vetiver hedges and trees should be planted along the top of the entire mine face to soak up and armour against high surface flows of water, and reduce rapid infiltration during storms.

Photo 29: *Hoses are sometimes used to deliver water for on-site process operations; a major challenge and cost for miners*

Apart from the present water supply, the main Butuzi site appears to have no major cracks in the earth where unstable land under tension is pulling away from the mountainside. Tarps may be laid over the cracks in locations where this is the case, with the top margin of the tarp dug diagonally down into the surface soil to capture all surface runoff and ephemeral streams. The bottom margin of the tarps should be lined with plastic water channels that feed rainwater storage cisterns located as far from the disturbed slope as is practical.

The above mentioned tension crack runoff diversion water systems and cisterns could feed sluicing and amalgamation stations far away from the disturbed site, thereby reducing the exposure of miners to slope failure without making them haul their ore uphill. Care should be taken to make properly armoured, well drained trails to these safe areas to avoid creating new stability hazards. Vetiver and trees should be planted along the trails and around the processing areas to reduce erosion.

Photo 30 and 31: *A recent landslide following heavy rainfall destroyed several mining tunnels*

Another significant geotechnical risk is that the unplanned, unmapped, and haphazard tunnelling further weakens the slope overall, and presents serious risk of tunnel collapses from miners burrowing under each other without knowing it. Even without such collapses, the inadequate buttressing of underground workings (made worse by the poorly consolidated and heterogeneous host rock) has already caused several collapses. Miners pointed out several mine openings that had collapsed. At least two tunnel collapses have closed off underground accesses since re-initiation of operations in 2010. Relatively straightforward measurement and mapping of the existing mine tunnels can be made using a hip chain and compass. By tracking excavation progress, miners can be alerted when they are in danger of compromising each other's workings.

Photo 32: *Hand dug channels are an important cause of slope instability*

6. Some: Forest degradation and biodiversity loss

Biodiversity loss

In Some, deforestation and biodiversity loss is potentially even a greater environmental concern than mercury contamination. Since artisanal mining is taking place in a primary tropical rainforest, with its wealth of biotopes and numerous species, it is important to be mindful of its wider environmental footprint. The Ituri Forest is renowned for its outstandingly diverse flora and fauna. It is the prime habitat of the Okapi, an endemic forest giraffe that is a national DRC symbol. Other spectacular and endemic forest species include the bongo, dwarf antelope, forest buffalo, forest elephant, the giant forest hog, the aquatic fishing genet, and chimpanzees. It is also an exceptional area for birds, including the endemic Congo Peafowl.

As noted earlier, the location of the Some site within the designated 50-km buffer zone of the Okapi Wildlife Reserve poses a specific risk. In effect, the Reserve is potentially at the receiving end of mercury pollution loads as it lies downstream of the Some site along the Ituri River. This creates a risk of mercury bioaccumulation in the tropical food chain from bacteria to carnivorous fish to animals feeding on fish and further to humans.

Primary impacts of artisanal mining on wildlife stem from habitat loss caused by vegetation removal and land degradation. The resulting habitat fragmentation is likely to disturb the home range and migration paths of wildlife. The risk of human-wildlife conflict and the spread of zoonotic diseases increases as animals are displaced and search for new habitats. Miners may also become opportunistically or deliberately involved in wildlife poaching. In addition, mining camps, which overtime may grow into villages, are likely to become centres for bush meat consumption and trade. Ivory trade, which has exploded across north-eastern DRC in the last several years, is another major issue of concern.

The high conservation value of the Ituri rainforest creates a challenging context for the roaming approach to mining in Some. The general trend of encroaching artisanal mining both within the ORW and its buffer zone further complicates the situation. Moreover, this pressure is likely to continue to increase with the steady immigration of people from the densely populated highlands.

Deforestation

In Kafiawema, miners found a gold vein under their mining camp and so they destroyed several hectares of forest to establish a new camp. Miners in effect clear-cut the forest, whereby all the trees in the camp area are cut-down with only a small number of trees left standing. Environmental impacts of clear-cutting range from soil erosion and increased risk of flooding to depletion of the carbon sink and modification of the micro-climate. Remote sensing could be used to monitor the evolution and extent of deforestation caused by artisanal mining.

Map 12 and 13: *Satellite imagery taken in April 2013 (above) and August 2015 (below) reveal expansion of deforestation patches and alluvial mining pits in the Mbembese area of the Some mining site. Google Earth imagery*

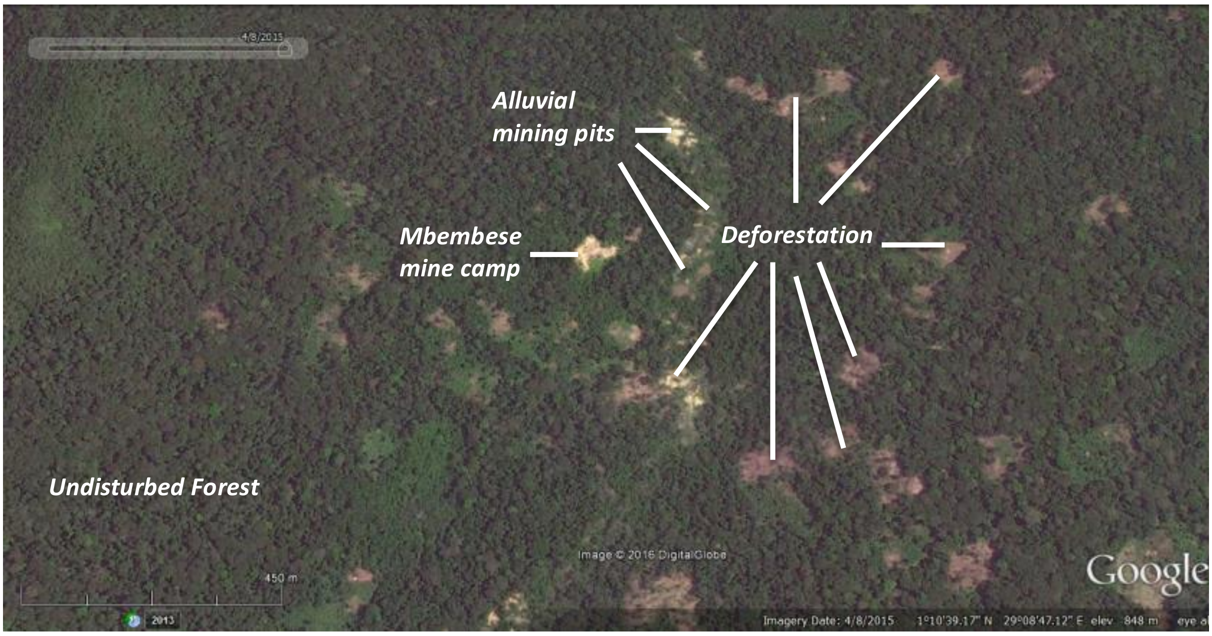


Photo 33: *On the edge of the rapidly shrinking climax equatorial rainforest, miners slash and burn valuable timber*

Mitigation of land degradation

Serious legacy problems from previous workings were also observed. In the Some area, extensive alluvial pits arrayed in a disorderly manner and never refilled dot the landscape. This creates stagnant ponds that prevent proper forest regeneration and vastly increase the potential for methylation (and therefore mobilization of more toxic and bioavailable mercury compounds) of legacy mercury contamination contained within the tailings and pond bottoms left by previous mining activities and augmented by present mining activities that discharge into these old mine holes. While addressing these complex environmental issues is beyond the immediate scope of the 'Just Gold' project, a sustainable mining model needs to progressively design a win-win solution that balances the interests of miners with that of the Reserve and its surrounding landscape. It should also be underlined that in order for remedial measures to gain the buy-in of miners, and be disseminated and replicated to other sites, technical solutions proposed must be affordable.

Mitigating measures to address the above mentioned impacts may be promoted through the project's agreement with miners on provision of technical assistance. This may include specific provisions promoting:

1. Systematic reclamation and backfilling of mined-out pits. Holes containing mercury contaminated tailings should be covered with one meter of clay or laterite, compacted, covered with soil, and re-vegetated.
2. Restrictions on wildlife hunting and trade including respecting national regulations on endangered species and the hunting season.
3. Selective approach to felling trees informed by technical assistance on mining exploration and planning.

To incentivize miners to gradually implement environmental improvements, the project may consider offering an 'environmental premium' and/or additional technical assistance for miners who demonstrate environmental compliance. Market-based initiatives for 'green gold' (e.g. Fairtrade and Fairmined gold) may be leveraged to help the project in incentivizing better environmental practice. Such initiatives should be undertaken in a gender inclusive perspective. Targeted outreach and follow-up will also be necessary to drive miners toward environmental improvements over the short and medium term.

Photo 34: *Having paid an illegal logger to fell hundreds of cubic metres of African Mahogany and other tropical hardwood on his day off, miners purchase sawn wood and carry it into camp*

7. Mining exploration

For every million-ounce scale deposit that would interest industrial miners there are thousands of surface deposits that could feed generations of artisanal miners. Artisanal miners generally explore at the margins of existing deposits by making test excavations and panning small samples to check for visible gold. Many just work for others who have some ownership or management of the mines. Mapping out the real social structures and organizational arrangement is beyond the scope of this environmental assessment, but is an important topic that needs to be studied, especially as it has important implications on the adoption of improved environmental practices by miners.

Miners will expand favourable excavations into a mine and continue as long as they can meet or exceed their daily needs. They do this either by opening up more surface deposits laterally, or by chasing deposits deeper into the ground by digging tunnels. Their approach should be expanded to include exploration, mine closure, health and safety, and mine planning. Tunnels are created without a thought to ventilation, stabilization, or the location and extent of other tunnels. This leads to collapses of tunnels that undermine each other, in addition to natural ones. Speleological surveys of tunnels are needed for tracking and avoidance of man-made cave-ins.

Photo 35: *Opening new ground for exploitation. Technical guidance is needed to help miners locate gold deposits and plan extraction accordingly*

Miners already have limited systems to organize forward thinking work that does not immediately produce gold. For example, a large number of workers in Butuzi were observed excavating overburden in search of new gold ore at the margins of existing workings. Furthermore, in Kafiawema many miners were working to open new excavations and buttress deeper parts of their mine pit. This system for organizing "unproductive" but necessary roles within the mining group should be studied for possible support of expanded "unproductive" roles such as exploration and waste management. Not only are these essential roles in a more orderly, formal, and environmentally responsible mining operation but they can also counterbalance the unemployment that can be generated when replacing inefficient methods with best practice mineral processing methods.

Photo 36: *Steep slope mining in Butuzi poses serious risks of landslides which could dam the Luzinzi River below*

8. Occupational safety

Working in the Butuzi and Some mine sites is a high risk and dangerous activity. This is due to both the site terrain (steep mountain slopes, inadequately buttressed tunnels, deep open pits, hazards from working in area covered with felled trees), risk of mercury poisoning, and the very limited use of personal protective equipment (PPE) by miners.

Photos 37*: Steep-slope mining is dangerous work*

Some basic measures and practices can be introduced to improve working conditions which should be accompanied with provision of appropriate training and information. This includes:

1. Using wheelbarrows or hand carts to haul the ore bags.
2. Wearing strong gloves (preferably non-latex) when handling mercury, particularly during tailing reprocessing and in whole ore amalgamation. Gloves should normally be used during all wet work.
3. All mercury should be stored in durable containers that are clearly labelled as mercury and as toxic, and covered with a layer of water to prevent the mercury from evaporating.
4. Putting on disposable dust masks and eye protection when dry milling rock ore. Note dust masks need to be regularly replaced.
5. Safety helmets should normally be worn at all time in the site, particularly in Butuzi.
6. Provide simple first aid equipment at the mine site.
7. Encourage miners to store clean drinking water and construct a sanitary pit latrine at the mine site.

Photo 38: *Steep-slope mining is dangerous work. Safety helmets and use of protective personal equipment are lacking*

9. Barriers to formality and the artisanal mining poverty trap

Artisanal miners tend not to explore for gold deposits, but instead congregate in sites where gold is already being produced. Globally speaking, most known gold deposits are usually orphaned mine sites, many of which were established in colonial times and are largely exhausted, though the remnant deposits are still suitable to those seeking a way out of poverty. Some deposits were singled out for international mining exploration programs whose development did not proceed for lack of economic justification or social license, and that were then taken over by miners that were alerted to the site by the presence of these prospectors. Perhaps more commonly, however, industrial mining prospectors identify potential mineral targets by seeking out artisanal mining sites and using their excavations and tunnels to assess potential ore bodies. Prospectors then proceed to purchase the mineral rights from the government or the legal title holder, without the knowledge of artisanal miners operating on site. They then pressure the government to use police and military forces to enforce their title rights by removing the 'invaders.'

Artisanal miners are often seeking entirely different deposits from those of interest to large mining companies, or different parts of the same deposits. Artisanal miners chase shallow ore in sparse and well defined high grade veins (in hard rock mining) or strata (in alluvial mining) that require little investment in excavation and mechanization to operate. Large companies use those deposits to identify and constrain larger, deeper, lower average grade deposits whose mine life production would justify massive capital expenditures required to exploit the ore for least cost and highest returns. Often industrial mines remove the "overburden" (overlying 'waste' rock that artisanal miners would exploit) in order to access the deeper industrial scale deposit with a large open pit. They take a full life cycle approach to mining operations, in which the cost of exploration, excavation, processing, waste storage and management are compared against the net value of the exported lifetime production.

Government regulations, particularly mineral title licensing rules, are often structured to favour large industrial mining operations. Obtaining mineral title is often the first obstacle encountered by any artisanal mining project aiming for transparency, formalization, or sustainability, and globally remains a vexatious and difficult barrier. Governments in Peru, Colombia, Mongolia, Guyana, and Suriname (among others), as well as in the DRC, are actively wrestling with this challenge with limited success due to the misinformation and competing interests that attend national level policy change initiatives.

In well-functioning property rights regimes, mineral titles expire if the title holder makes no investment in exploration or exploitation in the site. Where corruption and loopholes allow, titles are often renewed or held indefinitely, and all of the known and most promising mineral concessions are already claimed. Therefore artisanal miners are often immediately labelled "illegal miners," or, where their profits are funnelled to organized crime and conflict groups, "criminal miners." This is usually a gross oversimplification (artisanal and small scale miners in Colombia fund criminal groups involuntarily through extortion), but the perception drives government assemblies to set unrealistic legislative barriers to formalization and development of the artisanal mining sector. As a result, miners cannot enter the formal economy because they cannot obtain legal title to the deposits they are already working and are unable to negotiate equitable agreements with existing concessionaires.

Where miners have entered formal contracts with legal concessionaires, their lack of legal knowledge or counsel can produce abusive agreements that strongly favour the concessionaire and establish feudal arrangements that perpetuate dangerous, inefficient, and polluting practices while concentrating excessive wealth in the hands of distant title holders. In these cases, they also typically control the mercury supply and therefore may see its reduction as a diminished income. Furthermore, artisanal miners typically lack the skills and resources to explore available concessions, which are usually so remote or insecure as to make access difficult (and therefore provide secure funding sources for illegal or conflict groups).

An artisanal and small scale mining legal loophole

A transparent gold supply is, by necessity, a legal one. Legal gold by definition comes from operators of legal concessions, therefore formalization and mineral title are the highest order priority for any gold transparency program. Congolese provincial governments are currently managing artisanal mineral titles under a legal loophole: an ingenious reinterpretation of provincial jurisdiction concerning aggregate mining.

Aggregates are non-metallic rock deposits that are mined for road fill, concrete production and other construction activities. The non-metallic designation is usually clearly specified in aggregate mining legislations, so the present work-around may not be an intentional regulation. In other ways, artisanal operations are quite similar to aggregate mining, mainly in the sense that they are often mining poorly or un-consolidated materials that are close to the surface with a limited surface footprint. Therefore aggregate concessions are by definition small, shallow, cheap, and available. Where they overlap with centrally administered precious metals concessions, there are no real conflicts of interests because the large scale miners are not interested in the surface deposits other than as indicators of deeper potential strikes. This differentiation is less clear when considering alluvial and medium scale mining operators.

Kafiawema is a good example where aggregate concessions are used for semi-legal precious metals exploitation. One member of the community was digging a pit latrine and found a gold bearing vein. Rather than obtaining a national gold mining concession which would have required travel to Kinshasa with no certainty of being able to afford the licensing fee (in part because the minimum concession size may be prohibitive, and in part because gold is more valuable than aggregate), the miners in Kafiawema acquired an aggregate license. The project needs to further investigate national and provincial mineral concession legislations and para-legal functional agreements under which miners operate.

Loopholes that misuse provincial concession rules to circumvent federal ones may be a useful starting point from which to identify and harmonize the concession rules and establish a clear, equitable, achievable, and fully legal concession system that is accessible to artisanal miners. Jurisdictional conflict could be resolved by defining clear rules for industrial sector prospectors and developers wishing to operate concessions where small artisanal concessions overlap centrally administered concessions. One of the goals of artisanal mining development organizations is to find a way to establish formal agreements among industrial and artisanal mining groups where their interests are in potential conflict (even though they are interested in different parts of the deposit). This kind of harmonized legislation could be a first step toward that goal, though it might also reduce potential international investment because the industrial sector is afraid of the liability issues concerning partnerships with the informal sector. Gran-Colombia Gold in Segovia, Colombia, is one example of a successful relationship between sectors, and Barrick Gold's operations in Tanzania offer a useful case study in the formal sector's worst scenarios. The latter case is more representative of relations among artisanal and industrial miners globally.

The insecurity and disorganization of informality prevents miners from investing in exploration or best practices for fear of eviction and seizure by authorities. It forces an opportunistic, migratory, and marginal lifestyle on miners and traps them in poverty. This project needs to investigate and ensure the true legality of the mining claims in which they are operating, and use success cases to design and promote the review and reform of national mining and provincial regulation so that it better and more realistically serves both artisanal miners and the state.

10. Conclusions and recommendations

This study shows that mercury can be significantly reduced and ultimately eliminated by replacing the need for mercury by artisanal miners processing the ore. The strategy should be based on prioritizing pre-concentration before amalgamation. Efficient pre-concentration incurs gold losses, so processing in all parts of the chain needs to be improved including from: exploration and planning of deposit extraction and mine workings, choice and pre-processing of ore, efficient grinding for gold liberation, as well as concentration and monitoring of gold in ore and waste. Overall, higher gold recovery can be achieved without mercury. Technology transfer and training is an important pathway towards that end, assuming not only formality but access to investment and services.

Summary of recommendations

In addressing the multiple environmental challenges at the two AGM sites, the recommendations are sequenced by interventions requiring the least investment and training, followed by progressively costlier and more complex changes that can be added when the miners are ready to take the next step. Consultations with miners and local communities will need to be organized to obtain their views and buy-in on the proposed interventions.

Mercury reduction

1. Promote use of retorts or fume hoods to recover mercury and reduce exposure and inhalation of toxic mercury vapours. Miners must stop using leaves as a retort.
2. Promote concentration and direct smelting as an alternative to whole ore amalgamation.
3. Improve water supply and waste management using impermeable reservoirs, refilling old mine pits, and reorganization of processing activities. This will isolate mercury releases and reduce infiltration of water into landslide initiation zones.
4. Analyze gold ore mineralogy to guide changes in processing methods for both milling and gravity concentration.
5. Optimize mill feed, speed, duration, and grain size control, also using participatory controlled trials (including installation and comparison of existing milling equipment).
6. Improve existing sluice practices by optimizing flow velocity, feed consistency and turbulence through participative, controlled trials on site.
7. Field test different mechanical concentration devices on site, beginning with shaker tables, spirals, blue bowls, and jigs, using short term trials of lab scale equipment (which can also be used to further upgrade primary concentrates to enable direct smelting).
8. Implement best practice wet milling and concentration processes. Potential options include using the Artisanal Gold Council Burkina Faso micro scale processing plant as a model[9].
9. Use trenching and panning (basic) and potentially also modern geophysical instrumentation (such as electromagnetic surveys or other) to study gold reserves and plan mining activities.

[9] See *AGC Burkina Faso Update report* and video film *Emploie l'Or Artisanal pour l'Aide au Développement.*

Slope stabilization (Butuzi)

1. Plant Vetiver grass (*Chrysopogon zizanioides*) to help stabilize the steep slopes of the Butuzi mine site.
2. Control drainage to minimize ground saturation and erosion.
3. Build a concrete lined cistern and rain collection system.
4. Establish sluicing and amalgamation stations far away from the disturbed site to reduce the exposure of miners to slope failure.
5. Map and plan tunnelling activities.

Forest and land protection (Some/Kafiawema)

1. Systematically reclaim and-backfill mined-out pits. Holes containing mercury contaminated tailings, should be covered with one meter of clay or laterite, compacted, covered with soil, and re-vegetated.
2. Restrict wildlife hunting and trade.
3. Employ a selective approach to felling trees informed by technical assistance on mining exploration and planning.

Occupational safety

1. Use wheelbarrows or hand carts to haul the ore bags.
2. Wear strong gloves (preferably non-latex) when handling mercury, particularly during tailing reprocessing and in whole ore amalgamation. Gloves should normally be used during all wet work.
3. All mercury should be stored in durable containers that are clearly labelled as mercury and as toxic, and covered with a layer of water to prevent the mercury from evaporating.
4. Use disposable dust masks and eye protection when dry milling rock ore. Note dust masks need to be regularly replaced.
5. Safety helmets should normally be worn at all time in the site, particularly in Butuzi.
6. Provide simple first aid equipment at the mine site.
7. Encourage miners to store clean drinking water and construct a sanitary pit latrine at the mine site.

Appendix 1: Laboratory analyses interpretation

Bottle samples
All values measured in mg/kg (equivalent to ppm). Canada soil quality guideline Hg = 6.6 mg/kg; Interim freshwater sediment quality guideline Hg = 0.17 mg/kg

Sample code	Description	Discussion of chemical analysis	Hg	As	Pb	Au
B 1 B	River west of market where gold buyers burn amalgam. 1-2m wide, high banks, resistant old channel basin. Sample consists of fine black sand with mica flakes. Sample 1-10 cm depth sediment underwater. Mugera River. Brown turbid, surrounded by agricultural fields.	Evidence of mercury contamination, as expected from being downstream of the gold buyers in the market that burn Hg. No other metals show elevated concentrations.	0.03	6	6.5	
B 2 B	BLANK sample bottled at Luzinzi river site (b3b)	This blank material was sand from a construction site in Bukavu. No significant metal concentrations present.	0.0085	1.8	7.4	
B 3 B	Luzinzi River composite sample, bimodal immature sediment braided river heavily reworked by AGM with Hg. Composite sample of quiet water sediments upstream near faster flow channel in slower channel in the middle of amalgamation area. Panning is done in faster flow nearby, but also lots upstream.	Hg levels reflect the fact that this entire river is an artisanal alluvial mine at this site and for several kilometres upstream. Arsenic levels are 100x guidelines.	0.064	710	15	
B 4 B	Lulinja River composite sample along 3 m length of quiet bend in river; eddy bank. River is bright brown turbid from upstream mining. Large black shale rocks make small rapids in the fast flowing river middle. Sediment is fine sand and mud, brown with black strata.	Less contaminated than Luzinzi River, still evidence of amalgamation upstream.	0.034	8.9	7.5	
B 5 B	Heavily worked miner build river braid channelling, moderate water flow, silty bottom. Composite sample.	Less Hg contamination than expected, and illustrative difference in mercury concentration as compared to the duplicate. Mercury variability far exceeds the variability in other elements because it is deposited and disturbed in patchy, haphazard ways by humans, whereas the other metal concentrations are	0.068	950	19	

Sample code	Description	Discussion of chemical analysis	Hg	As	Pb	Au
		more related to background and tailings discharge which produce more uniform signals.				
B 6 B	Duplicate of B5B	consistent metal concentrations in both samples, Hg varies more	0.091	860	20	
B 7 B	Butuzi mine site amalgamation pond. Muddy yellow with standing water. Several miners amalgamated in this pond at last visit 2 days previously, suggesting this is a daily occurrence.	As contaminated as an amalgam pond would be. Arsenic is surprisingly high.	3.6	4400	61	
B 8 B	Background sample. 50cm below surface 10cm into scarp face. Brown moist subsoil (B horizon) with sharp rocks and some roots. Top of Butuzi mine site.	Surprising amounts of mercury in the ore itself. Perhaps miners had been burning nearby. The next sample, B9B, is a better mercury background sample.	0.34	1900	28	
B 9 B	GPS marks mine entrance. Ore sample taken in tunnel ~40m deep according to miner who took the sample, but shaft is circuitous.	A better background sample for mercury because it came from 40m depth. Arsenic levels are very high.	0.018	3500	47	< 8
B 10 B	Another amalgamation pond sample	Typically high concentrations of Hg and As for amalgamation ponds at this site. Interesting variability among the ponds.	0.95	12000	82	
B 11 B	Amalgamation pond sample (composite mixed in the sample jar not plastic bag)	Arsenic is high in all ponds because it is concentrated with the sulphide minerals like pyrite, then is discarded with the concentrate after amalgamation.	0.74	14000	28	
B 12 B	Luzinzi river 5km north and downstream of Kaziba	Alarmingly higher mercury concentrations downstream of most of the mining activity. Is there some very near? Also interesting how the Hg is consistent with the concentration 2km further downstream.	0.2	430	12	
B 13 B	Luzinzi river 7km north and downstream of Kaziba	Curiously high mercury content	0.26	390	14	
B Conc	Concentrate sample from banana bark sluice	Very interesting that the Hg from this concentrate, which was not exposed to mercury, is still 15x higher than the bulk ore in sample B9B. It indicates that perhaps B8B reflects possible background concentrations in parts of this deposit after all.	0.27	5700	110	10-40

Sample code	Description	Discussion of chemical analysis	Hg	As	Pb	Au
mleaf	Leaves that were used to capture mercury during amalgam burn	Tens of grams of leaves as contaminated as this are produced and discarded daily at each mine site in Congo.	2200 0			
M - Ore	Quartz ore sample	Quite low levels of all metals other than gold. This gold value matches the lowest values of the geological ore sample analyzed in Canada.	0.008 2	62	8.1	13
M 1 B	Upstream of mine site. Clear brown quiet 2m wide creek very slow almost still, forested banks, muddy. Hand sampled composite by local person under supervision, samples from 2m length of river, various water depths, surface 1-10 cm.	Perhaps high Hg indicates previous mining in or upstream of this site has contaminated the sediment already, or the background levels are high. The blank sample seems to suggest high background regionally.	0.16	3. 1	5.4	
M 2 B	Composite sample in creek immediately upstream of intake for mine water supply. Tea coloured water with muddy bottom 4m wide with low to modest flow and old forested banks. Mbela river.	Perhaps high Hg indicates previous mining in or upstream of this site has contaminated the sediment already, or the background levels are high. The blank sample seems to suggest high background regionally.	0.11	7. 3	21	
M 3 B	Composite sample at the outflow of the mine diversion channel, 4-5 m wide, very slow flow with muddy bottom and shading forested banks. Translucent with moderate turbidity. Sabasaba creek.	Hg is 10x the background and upstream values	1.1	37	12	
M 4 B	Blank sample at site M3B, material was originally from a sun baked termite mound 1 hour away from Mambasa on the road from Bunia, far from major settlements.	Regional background mercury levels are modest	0.12	1. 8	6.2	
M 5 B	Sluice waste and amalgamation pond composite sample	Hg contamination as expected	6.6	13 0	23	
M 6 B	Composite sample at M5B site; 5-6 times reworked tailings (new Hg added each time)	As a duplicate of the previous sample, this again indicates how variable mercury concentrations in hotspots can be; all other metals are nearly identical in concentration.	3.3	11 0	16	
M 7 B	Upstream composite sample downstream of clothes washing spot, small muddy creek.	We later found out that this was originally where they did their sluicing and amalgamation.	5	13 0	20	

Sample code	Description	Discussion of chemical analysis	Hg	As	Pb	Au
M 8 B	Duplicate of M7B.	As a duplicate of the previous sample, this again indicates how variable mercury concentrations in hotspots can be.	0.94	54	7.7	
M 9 B	Background sample of mud from 3m depth in mine pit wall in afternoon shade. Mottled grey /brown/red mottled texture with quartz pebbles in it.	Local background Hg does seem to be high, consistent with regional background.	0.16	310	17	
M 10 B	Amalgamation pond composite sample Mbembese mine site.	High Hg consistent with long term amalgamation use in this pond.	26	180	52	
M 11 B	Old alluvial holes filled in with dark stagnant water, looks like marshes and lakes with tea coloured water. Composite sample of recently reworked tailings.	Perfect conditions for methylation: contaminated tailings in stagnant, anoxic ponds with high dissolved organic content.	3.6	100	20	
M 12 B	"Upstream" in the Mbutele creek. NB. This is all one big un-reclaimed alluvial mine disaster that ended about 3 years ago and is partly revegetated. This spot had a trickle of current, clear water that is tea coloured when deeper.	Clearly there is generalized legacy Hg contamination in this area, as indicated by the disturbed landscape.	0.65	7.7	5.9	
M 13 B	Open sandy/gravelly pit complex in which it was hard to find fines. Unreclaimed alluvial disaster.	Clearly there is generalized legacy Hg contamination in this area.	1.1	17	4.1	
M 14 B	Road cut sample ~5cm into cut face and ~1m below ground surface. Hard pebbly saprolite, red.	Another even more odd Hg enrichment in the soil. Local background is quite high.	0.41	4.1	18	
M 15 B	Illegible sample information. Probably a field duplicate of M13B	Exactly equal mercury content compared with m13b	1.1	48	9.5	

Swab samples

All values measured in micrograms (µg) per wipe.

Sample Code	Description	Discussion of chemical analysis	Hg	As	Pb
S 1 B	Northwest corner of Katudu market Kabiza, gold buyer hut 1.5 metres from burn site. Swabbed wall under roof.	Relatively high mercury contamination, as expected	1.7	0.77	0.54
S 2 B	Katudu market Kabiza, gold buyer hut 2.4 metres from burn site.	Modest Hg at a modest distance	0.42	< 0.2	13
S 3 B	Katudu market Kabiza, gold buyer hut 3.7 metres from burn site.	Less mercury farther away	0.22	< 0.2	3.7
S 4 B	East end of Katudu market, FIELD BLANK	Mercury free blank suggests that cross contamination is not an issue	< 0.2	< 0.2	1.9
S 5 B	East end of Katudu market roof pillar brick	Non-significant result	< 0.2	< 0.2	1.5
S 6 B	Katudu market, East and South end	This value is high for being on the opposite side of the market. Possibly there are other burn sites?	0.4	< 0.2	3.1
S 7 B	Katudu market East and North end	Non-significant result	< 0.2	< 0.2	< 0.2
S 8 B	Katudu market, middle North end near restaurants.	Non-significant result	< 0.2	< 0.2	< 0.2
S 9 B	Katudu market West and North end near gold market	Nearer to the burn area the concentrations of Hg rise	0.29	< 0.2	< 0.2
S 10 B	Market Luakabiri, roof pillar of market	Non-significant result	< 0.2	0.23	0.73
S 11 B	Inside Kabiza elementary school classroom, wall nearest market where gold buyers set up	Non-significant result	< 0.2	< 0.2	0.9
S 12 B	Duplicate of 11	Non-significant result	< 0.2	< 0.2	3
S 13 B	Wall and top of roof beam of school class room beside gold buyer huts in market.	Non-significant result	< 0.2	1.1	0.87
S 14 B	courtyard of gold buyer house, wall above burn site	Odd not to find Hg here. Perhaps as miners usually burn at the mine site and this person's charcoal fire is not any hotter, it does not emit significant amounts of Hg?	< 0.2	< 0.2	0.47
S 15 B	Inside wall of gold buyer house	Non-significant result	< 0.2	< 0.2	0.45
S 16 B	Inside burn room behind buyers house	Non-significant result	< 0.2	< 0.2	4.2
S 1 BUK	Near gold shop chimney at Hotel Mt. Kauzi, Bukavu	Clearly sponge gold with residual mercury is found here	7	2.6	0.4

Sample Code	Description	Discussion of chemical analysis	Hg	As	Pb
S 2 BUK	Shadowy wall space between gold shop and hotel near burn area.	Hg decreases quickly in the short distance from the last sample.	1.2	0.29	0.81
M 1 S	Amalgam burn site wall	Definitive evidence of health hazard. Hg is relatively low for being immediately above the burn site.	2.1	0.81	< 0.2
M 2 S	5 metres west of M1S, above amalgam burn area under the roof	Hg decreases rapidly as one moves away from the burn site	0.52	0.92	< 0.2
M 3 S	Swab of the inside mercury storage room of PDG's house, swabbed roof beams, under shelves, counter top and underside.	Mercury storage room is contaminated	2.9	0.46	0.41
M 4 S	Blank sample at M3S site.	Non-significant result	< 0.2	< 0.2	< 0.2
M 5 S	Duplicate of M3S	Again, duplicates show that Hg varies much more than other metals, but duplicates generally agree within 30% error.	1.9	0.36	0.52
M 6 S	Walls and roof beams above the PDG's burn site at covered porch of his house.	By far the greatest Hg content in dust is above the camp burn site at the PDG's house.	1200	4.9	0.83
M 7 S	Roof beams of kitchen hut where they burn amalgam	Much lower Hg than in the amalgam burn site adjacent, consistent with miners habit of burning on the front porch instead of in their hut.	69	0.89	0.28
M 8 S	Location of fire pit where amalgam was burned in open air, this is dust sample of 3 surrounding trees within 4 metres of the burn site.	Modest elevated mercury in dust	3.3	0.34	1.5

Appendix 2: Laboratory analyses results

All soil, sediment, ore, leaves and wipe tests samples were analyzed for mercury and other metals by Spiez Laboratory in Switzerland.

The following table shows samples with the most significant amounts of mercury, other metals and the gold ores.

Sample	Analysis / Matrix	Mass fraction	Swiss threshold (TVA[1])
M 6 S	Mercury / wipe test	1200 µg / wipe	-
M 10 B	Mercury / sediment	26 mg/kg	0.5 mg/kg
M Leaf	Mercury / leaves	2.2 %	-
B 11 B	Arsenic / sediment	14000 mg/kg	15 mg/kg
B Conc	Copper / concentrate	1100 mg/kg	40 mg/kg
B 9 B	Gold / ore	< 8 mg/kg	-
B Conc	Gold / concentrate	10 – 40 mg/kg	-
M - Ore	Gold / quartz ore	13 mg/kg	-

[1]Swiss regulation about wastes (Technische Verordnung über Abfälle)

Laboratory analyses results for wipe tests

UNEP Code	UA-2016-12	Cr µg/wipe	Mn µg/wipe	Co µg/wipe	Ni µg/wipe	Cu µg/wipe	Zn µg/wipe	As µg/wipe	Cd µg/wipe	Pb µg/wipe	Hg µg/wipe
S 1 B	-15	2.7	18	0.57	1.2	1.7	4.8	0.77	< 0.2	0.54	1.7
S 2 B	-16	< 0.2	< 0.2	< 0.2	< 0.2	0.25	0.87	< 0.2	< 0.2	13	0.42
S 3 B	-17	< 0.2	1.1	< 0.2	< 0.2	< 0.2	0.24	< 0.2	< 0.2	3.7	0.22
S 4 B	-18	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	1.9	< 0.2
S 5 B	-19	0.8	5.2	< 0.2	< 0.2	0.22	0.72	< 0.2	< 0.2	1.5	< 0.2
S 6 B	-20	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	3.1	0.4
S 7 B	-21	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
S 8 B	-22	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
S 9 B	-23	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.29
S 10 B	-24	0.41	9.9	< 0.2	< 0.2	0.28	1.8	0.23	< 0.2	0.73	< 0.2
S 11 B	-25	< 0.2	4.1	< 0.2	< 0.2	< 0.2	1.2	< 0.2	< 0.2	0.9	< 0.2
S 12 B	-26	0.34	8.5	< 0.2	< 0.2	0.21	3.1	< 0.2	< 0.2	3	< 0.2
S 13 B	-27	4.3	96	1	2	3	19	1.1	< 0.2	0.87	< 0.2
S 14 B	-28	< 0.2	1.5	< 0.2	< 0.2	< 0.2	88	< 0.2	< 0.2	0.47	< 0.2
S 15 B	-29	< 0.2	3.4	0.43	< 0.2	< 0.2	0.6	< 0.2	< 0.2	0.45	< 0.2
S 16 B	-30	< 0.2	4.8	< 0.2	< 0.2	0.27	510	< 0.2	< 0.2	4.2	< 0.2
S 1 BUK	-31	0.88	6.2	< 0.2	0.24	0.42	4.7	2.6	< 0.2	0.4	7
S 2 BUK	-32	2.2	11	0.21	0.42	0.49	1.5	0.29	< 0.2	0.81	1.2
M 1 S	-33	< 0.2	2.3	< 0.2	0.24	< 0.2	1.1	0.81	< 0.2	< 0.2	2.1
M 2 S	-34	< 0.2	2.1	< 0.2	0.25	0.26	0.41	0.92	< 0.2	< 0.2	0.52
M 3 S	-35	0.22	1.3	< 0.2	0.42	0.5	2	0.46	< 0.2	0.41	2.9
M 4 S	-36	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.55	< 0.2	< 0.2	< 0.2	< 0.2
M 5 S	-37	< 0.2	0.88	< 0.2	0.28	0.22	0.63	0.36	< 0.2	0.52	1.9
M 6 S	-38	0.66	6.6	< 0.2	0.85	1	2.2	4.9	< 0.2	0.83	1200
M 7 S	-39	0.48	28	< 0.2	0.68	1.2	4.4	0.89	< 0.2	0.28	69
M 8 S	-40	0.22	2.2	< 0.2	0.29	0.25	0.9	0.34	< 0.2	1.5	3.3

Laboratory analyses of mercury in soil / sediment / ore / leaf samples:

UNEP Code	UA-2016-12	Hg µg/kg dry matter
B 1 B	-1	30
B 2 B	-2	8.5
B 3 B	-3	64
B 4 B	-4	34
B 5 B	-5	68
B 6 B	-6	91
B 7 B	-7	3600
B 8 B	-8	340
B 9 B	-9	18
B 10 B	-10	950
B 11 B	-11	740
B 12 B	-12	200
B 13 B	-13	260
B Conc	-14	270
M - Leaf	-41	22000000 (2.2 %)
M - Ore	-42	8.2
M 1 B	-43	160
M 2 B	-44	110
M 3 B	-45	1100
M 4 B	-46	120
M 5 B	-47	6600
M 6 B	-48	3300
M 7 B	-49	5000
M 8 B	-50	940
M 9 B	-51	160
M 10 B	-52	26000
M 11 B	-53	3600
M 12 B	-54	650
M 13 B	-55	1100
M 15 B	-56	1100
M 14 B	-57	410

Laboratory analyses of other metals in soil / sediment / ore
mg/kg dry matter / l = leached ; t = total / * gold only informational values, not accredited

UNEP Code	UA-2016-12	Cr – l mg/kg	Mn- l mg/kg	Co – l mg/kg	Ni- l mg/kg	Cu – l mg/kg	Zn - l mg/kg	As – l mg/kg	Cd –l mg/kg	Pb – l mg/kg	U –l mg/kg	Au –t * mg/kg
B 1 B	-1	65	360	14	33	40	84	6	< 0.5	6.5	1.2	
B 2 B	-2	7.2	54	1.3	4.4	3	18	1.8	< 0.5	7.4	3.7	
B 3 B	-3	20	250	6.6	12	190	26	710	< 0.5	15	6	
B 4 B	-4	36	410	7.9	17	22	28	8.9	< 0.5	7.5	0.87	
B 5 B	-5	20	160	5.7	13	240	16	950	< 0.5	19	9.3	
B 6 B	-6	19	190	6	13	220	14	860	< 0.5	20	9	
B 7 B	-7	39	15	1	1.9	500	7.3	4400	< 0.5	61	60	
B 8 B	-8	69	42	1.1	2.5	170	7.3	1900	< 0.5	28	9	
B 9 B	-9	25	14	0.71	4.5	710	5.1	3500	< 0.5	47	72	< 8
B 10 B	-10	58	22	3.2	3.2	920	5.1	12000	< 0.5	82	120	
B 11 B	-11	47	21	3.2	3.1	770	8.4	14000	< 0.5	28	57	
B 12 B	-12	23	270	6.7	13	200	77	430	< 0.5	12	4.1	
B 13 B	-13	30	290	7.9	18	120	41	390	< 0.5	14	4.8	
B Conc	-14	36	40	5.6	11	1100	6.9	5700	< 0.5	110	44	Oct-40
M - Ore	-42	12	30	3.5	16	31	12	62	< 0.5	8.1	< 0.5	13
M 1 B	-43	31	130	8	12	7.4	25	3.1	< 0.5	5.4	0.56	
M 2 B	-44	100	480	27	37	21	75	7.3	< 0.5	21	1.1	
M 3 B	-45	24	140	7.6	13	11	25	37	< 0.5	12	< 0.5	
M 4 B	-46	46	400	13	17	16	25	1.8	< 0.5	6.2	0.59	

UNEP Code	UA-2016-12	Cr – l mg/kg	Mn- l mg/kg	Co – l mg/kg	Ni- l mg/kg	Cu – l mg/kg	Zn - l mg/kg	As – l mg/kg	Cd –l mg/kg	Pb – l mg/kg	U –l mg/kg	Au –t * mg/kg
M 5 B	-47	33	50	4	22	18	12	130	< 0.5	23	< 0.5	
M 6 B	-48	30	40	3.2	19	15	16	110	< 0.5	16	< 0.5	
M 7 B	-49	19	56	4.6	16	16	15	130	< 0.5	20	< 0.5	
M 8 B	-50	19	120	3.9	5.9	8.5	63	54	< 0.5	7.7	< 0.5	
M 9 B	-51	66	38	4.5	18	42	32	310	< 0.5	17	2.3	
M 10 B	-52	20	34	4.1	23	25	19	180	< 0.5	52	1	
M 11 B	-53	35	130	4.6	12	14	31	100	< 0.5	20	< 0.5	
M 12 B	-54	33	280	8.9	11	9.9	25	7.7	< 0.5	5.9	< 0.5	
M 13 B	-55	30	120	5	8.4	9.7	19	17	< 0.5	4.1	< 0.5	
M 15 B	-56	15	160	4.8	6.5	57	150	48	< 0.5	9.5	< 0.5	
M 14 B	-57	21	97	3.1	11	3.4	35	4.1	< 0.5	18	6.2	

Sinuous patterns from extensive reworking of the Luzinizi riverbed by artisanal miners

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