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PAPER

Assessment of environmental mercury discharge at a four-year-old artisanal gold mining area on Lombok Island, Indonesia

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Indonesian artisanal and small-scale gold mining activities (ASGM) have been described for the islands of Borneo (Kalimantan) and Sulawesi. But the increased gold price over recent years has seen operations extend to the islands of Lombok and Sumbawa. For the current research, an environmental assessment was conducted across three new ASGM locations. Gold is recovered by miners through a two-stage process of whole-ore amalgamation and cyanidation. Waste (tailings) is discharged to land or sea with no concern for contaminants in the tailings. The gold grade of ore is up to 5000 mg kg^{-1}. The mean gold grade of the amalgamation tailings is 7 mg kg^{-1}, dropping to 1.2 mg kg^{-1} for the cyanidation tailings. The mean mercury concentration of the amalgamation tailings is about 3000 mg kg^{-1} and greater than 1600 mg kg^{-1} for the cyanidation tailings. Samples of paddy rice grain collected adjacent to cyanidation tailings ponds showed methyl mercury concentrations greater than 100 ng g^{-1}. This is five times above the Chinese permissible level for total mercury in food crops. The mean total mercury concentration in hair of Lombok ASGM workers was greater than that in a non-exposed population; however there was no difference in methyl mercury concentration. This indicates the primary pathway of mercury exposure is inhalation of volatile mercury in the atmosphere. Future exposure may come from ingestion of methyl mercury contaminated rice where discharge of cyanide tailings to paddies continues. To protect the environment and to enhance the sustainability of ASGM, appropriate tailings management must be implemented. The gold grade of the tailings indicates that the residual value might be recoverable with appropriate technology. Ongoing research is investigating systems such as phytoextraction that might assist ASGM operators in Lombok and Sumbawa to improve their environmental performance.

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Introduction

Gold mining in developing countries can be organized and regulated, with mechanisms in place to protect workers and the environment. But mining can also be informal and small-scale, with minimal regulatory control of activities. This second form of mining is described as artisanal or small-scale gold mining (ASGM), and in Indonesia is known as PETI, an abbreviation of the term 'Pertambangan Emas Tanpa Izin'. Numerous health,

Environmental impact

Artisanal and small-scale gold mining (ASGM) began on the Indonesian islands of Lombok and Sumbawa in 2008. Environmental monitoring to date has been non-existent. A two-stage process of whole-ore amalgamation followed by cyanidation is practiced before mine waste is discharged directly to land or water. A mercury concentration in excess of 1600 mg kg^{-1} was recorded for cyanidation tailings during an initial environmental assessment described in this paper. Hair collected from an exposed population indicates that mercury exposure in Lombok is primarily the inhalation of mercury from air. However, cyanidation will readily dissolve mercury from rock mobilising the element to the soil–plant system with tailings. Levels of methyl mercury in rice growing adjacent to cyanidation facilities suggest that ingestion of contaminated food may be an exposure pathway of future concern.

environmental and social problems are typical of ASGM operations worldwide.[1]

A 2001 survey published by the International Institute for Economic Development estimated that 713 ASGM operations were in place throughout Indonesia.[2] The rise in the international gold price to over US$1600 per ounce by the end of 2011 has led to an increase in ASGM activity, although this increase is poorly quantified. Recent discussion has suggested that over 800 ASGM hotspots exist in Indonesia involving about 50 000 miners and 1 million people in total.[3] Most of these miners do not make large profits; they strive to make sufficient money to support their immediate family. However, each miner is thought to generate income for a further 10 people.[4] ASGM, therefore, represents a significant source of income for some of Indonesia's poorest people. But operations are often illegal and/or poorly regulated. Miners may have no title to the land they are working, and there is no incentive or provision for sustainable land management. Environmental destruction is the most visible outcome of artisanal mining. Environmental affects in Indonesia follow those in other parts of the world and include acid mine drainage, deforestation, soil erosion, river silting and the pollution of soil and water with toxic compounds.[1,2]

Mercury amalgamation is the most common method of gold recovery used by artisanal miners. This technique is favoured because it is considered by miners to be effective, easy to use, cheap, and mercury is readily available. However, mercury is highly toxic. Symptoms of human poisoning can vary from minor learning disability to extremely diminished mental capacity.[5] The United Nations Environment Programme (UNEP) states that there are serious long-term environmental health hazards in populations living in, near, or downstream/wind of artisanal and small-scale mining operations.[6] The greatest human health concerns are related to methyl mercury, which can bioaccumulate in the food chain, cross placental barriers, and act as a developmental neurotoxin.[1] Dissolved mercury species can methylate in the soil environment in the presence of anaerobic bacteria,[7] or through abiotic pathways.[8,9]

The use and cycling of mercury at ASGM locations has been extensively studied. It is estimated that between one and two grams of mercury is lost to the environment per gram of gold produced.[10] Worldwide this may lead to the annual release of up to 1000 tonnes of mercury to the environment.[11] Between 100 and 150 tonnes per year are estimated to be released from Indonesia, although some commentators believe this figure is too conservative.[3]

At many ASGM locations a two-stage process of amalgamation followed by cyanidation is used to ensure maximum recovery of gold from ore. Cyanidation is being promoted as an alternative to amalgamation by groups seeking to reduce the mercury consumption of ASGM (for example, by the efforts of the Global Mercury Project sponsored by GEF, UNIDO and UNDP). Throughout Indonesia the two techniques are used sequentially. Cyanide is very effective at making gold soluble, but will also complex with mercury (and other heavy metals) present in the amalgamation tailings being leached. The bioavailability of mercury is increased through cyanidation, and when discharged into the environment shows increased potential to biomethylate and enter the food chain.[12,13]

There is a good published record of ASGM operations in North Sulawesi and Kalimantan with some record of activities in Western Java. These studies have investigated the efficiency of gold recovery,[13] as well as the effects of mercury on the environment and people.[14–16] However, the current work represents the first published record of ASGM activities in West Nusa Tenggara (WNT) province, where mining has only begun within the past four years. This paper contributes to the discussion on ASGM by reporting the grade of gold as well as mercury in mine wastes (tailings), presenting a preliminary report on the extent of recent ASGM activities in WNT province that should facilitate more detailed surveys in the region. The hypothesis of this study is that ASGM operations have released mercury into the environment through the uncontrolled discharge of mine tailings at the end of mining. The gold concentration in ore and tailings, and the mercury concentration (total and/or methyl mercury) in ore, tailings, rice leaf and grain, and human hair, were determined in this research. No attempt was made to analyse the extent of mercury contamination in the atmosphere.
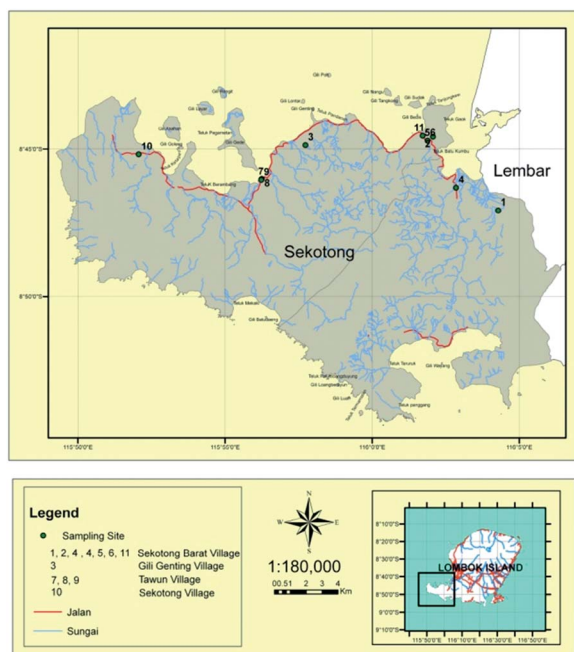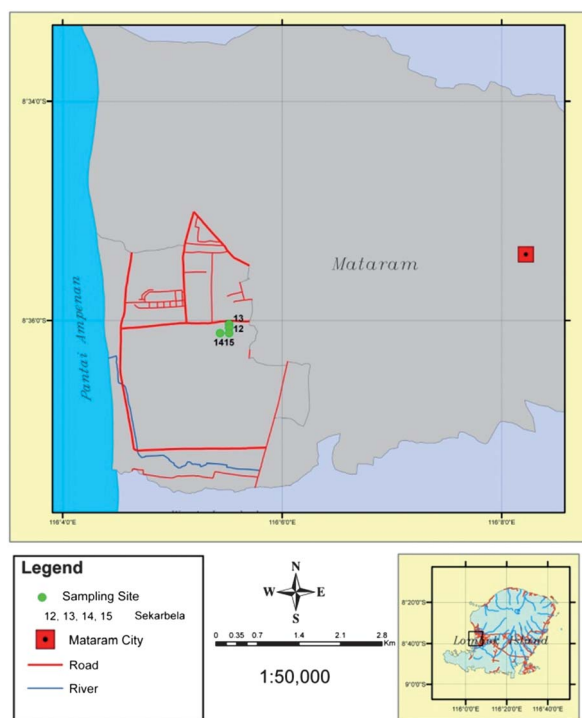
Methods and materials

Research location

The research was conducted through a field survey of the Sekotong (south west Lombok; Fig. 1), Sekarbela (near Mataram city, Lombok; Fig. 2) and Sumbawa Besar (Fig. 3) ASGM areas of WNT province during February 2011. During a one-week period, each mining area was visited, and random operations selected for sampling. Artisanal and small-scale gold processing throughout this part of Indonesia consists of discreet and small-scale processing units that receive ore brought from mining shafts. Eighteen separate locations were sampled across the three mining areas. Two types of operation were visited; amalgamation facilities, and cyanidation facilities (Fig. 1–3). Primary ore for amalgamation, amalgamation tailings for cyanidation, and cyanidation tailings were available for sampling in the three areas. On Lombok, hard-rock mining occurs throughout the Sekotong region, with ore transported as far as the capital city Mataram for processing (Sekarbela). But in Sumbawa, amalgamation and cyanidation facilities have been constructed close to the points for ore extraction. The extent of mining activity is increasing in both Sekotong and Sumbawa.[17]

Sample collection

Primary ore and/or tailings samples were collected at each sampling location (Fig. 1–3). Amalgamation tailings were collected directly from the amalgamation facilities, but also from cyanide facilities, as amalgamation tailings represent the ore for cyanide leaching. Ore and amalgamation tailings were collected from sacks using a small metal shovel, while cyanidation tailings were sampled directly from tailings dams. Triplicate samples of ore were collected from sacks at nine amalgamation facilities on Lombok and two on Sumbawa. Twenty-five samples of amalgamation tailings were collected from sacks at 14 locations on Lombok, and eight samples from sacks at three locations on Sumbawa. A total of 63 samples of cyanidation tailings were collected from four cyanidation tailings dams on Lombok, and three samples from a single dam on Sumbawa. Where it was

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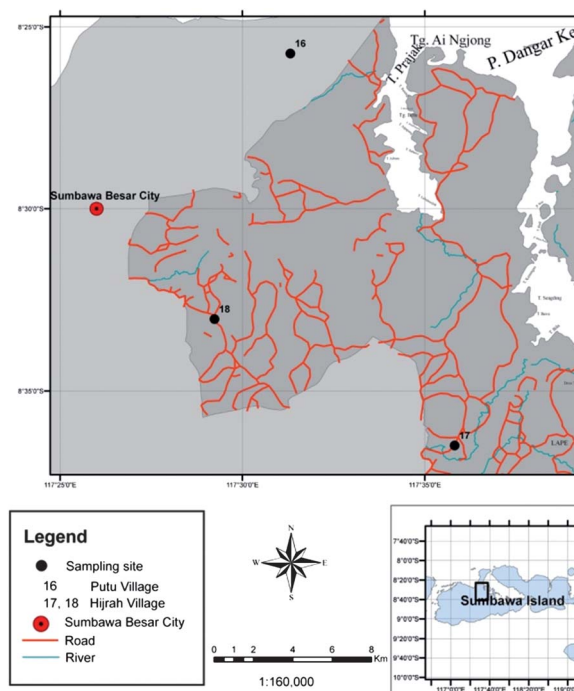J. Environ. Monit., 2012, 14, 2598–2607 | 2599

Fig. 1 The Sekotong ASGM area and record of the locations sampled in this research. Locations 1, 2 and 3 are cyanidation facilities. The remaining locations are amalgamation facilities.

Fig. 2 The Sekarbela ASGM area and record of the locations sampled in this research. The four locations are amalgamation facilities.

Fig. 3 The Sumbawa ASGM area and record of the locations sampled in this research. Locations 16 and 18 are amalgamation facilities. Location 17 has multiple amalgamation and cyanidation facilities.

between samples, the shovel and corer were washed in water between sampling locations. Sample size was a minimum 100 g and, in some cases, up to 1 kg wet weight. Duplicates of every sample (including triplicates) were collected and placed in labelled polyethylene cliplock bags for transport to the laboratory.

At two cyanidation locations (1 and 3; Fig. 1), ten replicate samples of rice plant material were collected from an adjacent rice paddy. At location 1, the rice crop had set seed, so samples of edible rice grain could be collected. At location 3, only leaf material from rice plants could be collected. All plant samples were collected in paper envelopes.

As part of the study, an initial health survey of workers was conducted. A total of 40 volunteer participants at sampling locations across Sekotong and Sekarbela (the exposed group) answered a short questionnaire, and allowed the sampling of hair for subsequent analysis. Hair samples were cut with stainless steel scissors from the occipital region of the scalp and sealed in polyethylene bags for transport to the laboratory. Two replicate hair samples were collected from each individual. A control group of 40 individuals were randomly selected through visiting areas away from the mining activity. The control group were subject to the same questionnaire and hair sampling. The control population came from both the Sekotong area and from Mataram city. Participants were discounted from the control group if they had any involvement or association with mining.

Sample preparation

Upon return to the Lombok laboratory (University of Mataram), samples were checked against the record list. Of the two substrate replicates collected, one set was packaged and

possible to walk across the cyanidation tailings dam surface (locations 1, 2, 3; Fig. 1), samples were collected at four depths using a stainless steel corer with internal diameter of 2.5 cm (0–7.5 cm, 7.5–15 cm, 15–23.5 cm, 23.5–30 cm depth). To mitigate the risk of cross-contamination of mercury and gold

transported to Massey University in New Zealand for total gold analysis. The other replicate was packaged and transported to Brawijaya University in Indonesia for total mercury analysis. Upon receipt in each laboratory all substrate samples were air dried. Tailings samples were homogenised using a mortar and pestle. Ore samples were ground using a ring grinder. Plant material was rinsed under running water in the Lombok laboratory, then air dried in paper bags for transport to the Institute for Geochemistry in Guiyang, China for methyl mercury analysis. Once in China, the rice grain was separated from seed hull for samples collected from location 1 before both plant parts were analysed for mercury. Hair samples were also transported to China. One replicate was analysed for methyl mercury concentration, the other for total mercury concentration. Once in China, hair samples were washed with non-ionic detergent, distilled water, and acetone, and dried in an oven at 60 °C overnight.

Analytical methods

Total gold analysis of ore and tailings samples was performed in the Soil and Earth Sciences Group Research Laboratory, Massey University, Palmerston North, New Zealand using graphite furnace atomic absorption spectroscopy (GFAAS; Perkin Elmer AAnalyst 800) following the method of Anderson et al.[18] Subsamples of ground tailings and ore (1 g) were digested in borosilicate tubes with aqua regia (10 mL; analytical grade nitric and hydrochloric acids) for 2 hours at 120 °C using a heating block. The resulting digest solution was made to 20 mL and then filtered (Whatman no. 42). An aliquot of the aqueous solution was quantitatively extracted into methylisobutyl ketone, and the organic fraction analysed for total gold concentration. The limit of detection for gold in solution following the described methodology was 0.5 ng mL^{-1}. The gold absorbance from replicate analysis ($n = 10$) of a 10 ng mL^{-1} gold standard solution was reproducible with less than 5% variation.

Total mercury analysis of ore and tailings samples was performed in the laboratory of the International Centre for Management of Degraded and Mining Lands at Brawijaya University using cold vapour atomic absorption spectroscopy (CVAAS; Hua guang model F732-S, China). The method of Moreno et al.[19] was followed for substrate analysis. Sub-samples (1 g) were pre-digested overnight, at room temperature, with aqua regia (15 mL; analytical grade nitric and hydrochloric acids) in borosilicate beakers. The following day the preparations were digested at 120 °C for two hours. Deionised water was then added (20 mL), the digest solutions filtered (Whatman no. 42), and then made to 100 mL. Ten mL aliquots were analysed with 1 mL of 5% nitric acid and 1 mL of freshly prepared SnCl$_2$ (10%) as the reducing agent. Sequential 1 : 10 dilutions were performed in nitric acid (5%), where necessary, to yield an absorbance on the standard curve. The limit of detection for mercury in solution following the described methodology was 0.1 ng mL^{-1}. The mercury absorbance from replicate analysis ($n = 10$) of a 10 ng mL^{-1} mercury standard solution was reproducible with less than 5% variation.

Analysis of hair and plant samples for methyl mercury, and hair samples for total mercury, was performed at the State Key Laboratory of Environmental Geochemistry in Guiyang, China.

Sub-samples of rice plant (0.2–0.5 g) or hair (0.1–0.3 g) for methyl mercury determination were digested using a KOH–methanol/solvent extraction technique.[20] After completion, the digest was acidified with concentrated hydrochloric acid. Methyl mercury in the digest solutions was extracted with methylene chloride, back-extracted from the solvent phase into water, and in the later phase ethylated. The ethyl analogue of methyl mercury, methylethyl mercury ($CH_3HgCH_2CH_3$), was separated from solution by purging with N$_2$ onto a Tenax trap. The trapped $CH_3HgCH_2CH_3$ was then thermally desorbed, separated from other mercury species by an isothermal gas chromatography (GC) column, decomposed to Hg^0 in a pyrolytic decomposition column (800 °C), before being detected by CVAFS (Brooks Rand Model III, Brooks Rand Labs, Seattle, WA, USA) following USEPA method 1630.[21] The operating detection limit for methyl mercury was 0.003 ng g^{-1} in rice and 0.002 ng g^{-1} in hair samples. The absolute limit of detection for methyl mercury using this methodology is 0.1 pg. Hair samples for total mercury determination were directly measured (solid sample) using a Lumex RA915+ mercury analyzer equipped with a PYRO 915+ pyrolysis attachment by way of thermal decomposition to Hg^0. The detection limit of the instrument was 0.2–5 ng g^{-1}. The mercury absorbance value from replicate analysis ($n = 7$) of a certified reference material (GBW09101b, Table 1) with total mercury concentration of 1060 ng g^{-1}, was reproducible with less than 5% variation.

Analytical precision and quality control

Reagent blank solutions were analysed in parallel with samples and were below detection for each determination. Linear calibration curves over the range 0 to 50 ng mL^{-1} for gold, and 0 to 10 ng mL^{-1} for total mercury (Indonesia), were prepared from 1000 mg L^{-1} standard solutions (Merck CertiPUR) for spectrophotometer determinations. A quality control (QC) procedure was implemented for all components of the analytical study by using parallel standard reference materials (SRMs). A summary of the QC procedure for this work and the percentage recovery from each SRM is presented as Table 1.

Table 1 Description of the standard reference materials used as part of the analytical quality control procedure for the current study

Parameter	SRM used	% Recovery
Total Au	PTM 1a (Natural Resources Canada) noble metal-bearing copper–nickel matte	85%
Total Hg (sediment – Indonesia)	CRM051-050 (Resource Technology Corp., USA) clay reference material for trace metals	>80%
Total Hg (hair – China)	GBW09101b (Chinese national standard reference) hair reference material for trace metals	>96%
Me-Hg (hair)	TORT-2 (National Research Council Canada) lobster hepatopancreas reference material for trace metals	>92%
Me-Hg (plant)	TORT-2 (National Research Council Canada) lobster hepatopancreas reference material for trace metals	85%

Data analysis

All sample data was processed using Microsoft Excel. Provisional statistical testing was conducted using Excel. Where statistical differences were apparent between means, or where data correlations were apparent, further statistical investigation was performed using SAS 9.1.2 statistical software (SAS Institute, Cary, North Carolina).

Results and discussion

The artisanal mining system in WNT province

Mining at the Sekotong, Sekarbela and Sumbawa locations generally follows the system described by Veiga et al.[13] for North Sulawesi, although mining in WNT is perhaps even less regulated due to the onset of activities over only the past four years. Mining techniques are essentially unchanged from those reported by Limbong et al.[14] to be occurring in 2001 in Kalimantan. This is despite technology advances that have been adopted at some worldwide ASGM locations over the past ten years. There appears to be no government effected restriction on the illegal sale or use of cyanide. Any pressure to limit the use of cyanide may be coming from mining companies exploring in the area. At both locations rock is removed by hand from simple mine shafts, and transported from the mining sites in sacks (generally 20 kg). These sacks are sold to processors who grind the rock at locations throughout Lombok and Sumbawa with water in simple rod mills (gelondong). There is no grade control or assurance of gold content in the rock. The purchaser of the rock makes a gamble that there will be some gold present. Fraud is likely commonplace with sacks of rock filled from the road side being reportedly sold by some miners. The whole ore is milled, with no attempt at concentration of the contained gold. Mercury is added during the later stages of grinding, and the amalgam is panned off. Artisanal miner reports indicate that each sack of rock is ground with mercury three times to ensure maximum removal of gold. The amalgam is squeezed through cloth to separate excess mercury which is recycled, and the final amalgam ball is sold to gold buyers, with a price determined by weight and purity. Local buyers heat the amalgam using gas burners to leave the pure metal. The infrastructure for smelting varies from open air pans to constructed heating chambers, although there is no apparent effort to collect volatilised mercury. There was no evidence for the use of retorts during the period of field research. Pure gold is eventually sold to goldsmiths in Mataram city.

It is difficult to fully track the fate of the amalgamation tailings. It appears that a large proportion of the tailings are sold to cyanidation plants that dispatch agents to travel the roads of the mining areas collecting sacks of this waste product (US$2 per 20 kg sack of tailings in Feb 2011). However, it seems likely that some proportion of the tailings is discharged into creeks, rivers, the sea, or onto land. There is no regulation controlling the disposal of the tailings. Presumably where there is money to be made by preserving the tailings (i.e. on-sale to cyanidation plants), the tailings will be collected. However, where on-sale is not an option, tailings will be likely disposed of in the easiest or cheapest manner.

Cyanidation plants are present at the Sekotong and Sumbawa mining areas, although the exact number of facilities is unknown.

The plants may be owner-operated or toll processing facilities. In February 2011 toll operators were charging approximately US$300 per use (Sekotong), and on average 10 rentals could be accommodated per month. A tailings slurry is placed in the leaching tanks, calcium hydroxide is added to increase the pH, and sodium cyanide added to dissolve residual gold. Tanks generally contain 8000 kg of tailings at a water : tailings ratio of 1 : 3. The target pH of the leach is 10.5, and approximately 10 kg of cyanide is used per tank. Oxygen is sometimes supplied to the leach through compressed air lines. Agitation is effected using diesel-driven impellers within the leach tank. After a two-to-three day leach period, activated carbon (20 kg) is added to the tank and the leach continues. The carbon adsorbs gold from the cyanide solution. The content of the leach tank is then screened to remove the carbon which is rinsed and burnt in open drums. Gold in then recovered from the ash using a final amalgamation step. The barren cyanide solution and tailings is discharged through the screening process directly to adjacent land or to sea. In some operations, discharge to land is into rudimentary tailings ponds (excavated holes). But in many cases rice paddies receive the cyanidation waste.

Gold recovery at ASGM operations using cyanidation can be efficient (up to 95% recovery).[22] However, gold is not the only metal dissolved from the amalgamation tailings during cyanide leaching. Mercury will also form soluble complexes with cyanide, with the species dependant on pH; although the rate of dissolution of mercury in cyanide is slower than that for gold.[23] Velasquez-Lopez et al.[24] reported a mercury balance for a carbon-in-pulp cyanidation circuit of amalgamation ore in Ecuador, and showed that approximately 27% of mercury in the feed material was leached over three days. A portion of this complexed mercury will be discharged with the tailings, but a portion is recovered onto carbon.[24] During cyanidation operations in WNT province, mercury adsorbed onto carbon will likely be released into the atmosphere as the carbon is burnt to recover gold.

Gold and mercury grades across the Lombok and Sumbawa mining areas

A summary of the gold and mercury concentration recorded for the collected samples is presented in Table 2 (Lombok locations) and Table 3 (Sumbawa locations).

Table 2 Summary of the gold and mercury concentration in primary ore, amalgamation tailings and cyanidation tailings across the sampled Lombok locations. n describes the number of samples analysed. N describes the number of locations from where these samples were collected. All concentrations are reported as mg kg^{-1}

	Metal concentration (mg kg^{-1})		
	Mean ± SD	Max	Min
Primary ore n = 9 N = 8			
Au	88.6 ± 241	731	0.32
Hg	1736 ± 2666	8364	112
Amalgamation tailings n = 25 N = 14			
Au	6.89 ± 5.09	20.6	1.68
Hg	3002 ± 1964	7874	741
Cyanide tailings n = 63 N = 4			
Au	1.20 ± 1.04	6.58	0.41
Hg	1628 ± 1127	6615	103

Table 3 Summary of the gold and mercury concentration in primary ore, amalgamation tailings and cyanidation tailings across the sampled Sumbawa locations. *n* describes the number of samples analysed. *N* describes the number of locations from where these samples were collected. All concentrations are reported as mg kg^{-1}

	Metal concentration (mg kg^{-1})		
	Mean ± SD	Max	Min
Primary ore n = 5 N = 2			
Au	955 ± 2083	4680	0.51
Hg	299 ± 422	1021	nd[a]
Amalgamation tailings n = 8 N = 3			
Au	7.28 ± 6.54	19.29	1.68
Hg	2856 ± 1286	4587	811
Cyanide tailings n = 3 N = 1			
Au	1.17	—[b]	—
Hg	1953	—	—

[a] The report of nd for a minimum concentration shows that the mercury concentration was below detection. [b] No data analysis parameters are reported for the Sumbawa cyanide tailings as only one location was sampled (*N* = 1).

Lombok. The gold grade of the primary ore was variable, highlighting a lack of grade control. The range of gold grade was from a low of 0.32 mg kg^{-1} to a maximum concentration of 731 mg kg^{-1}. This maximum value is an extremely high gold grade, but is likely not reflective of the general ore body being mined. The mean gold grade was high (88.6 mg kg^{-1}), but this was associated with a large standard deviation as a result of the range of grade values.

The mean gold grade of the amalgamation tailings was lower than that of the primary ore (6.89 mg kg^{-1}), although the range was again large. There was some confusion during miner interviews as to the number of times the sampled tailings had been put through the amalgamation process. To simplify data presentation, no consideration has been given to the number of times that tailings have been processed. The mean gold concentration of the cyanide tailings was significantly lower than that of the amalgamation tailings, but was appreciable (1.20 mg kg^{-1}). This gold grade is economic for some modern mines. The maximum gold grade for the cyanide tailings was 6.58 mg kg^{-1}. There was no significant correlation of gold concentration with depth ($r = -0.1055$) where sampling of cyanide tailings was conducted at four depth intervals.

The data in Table 2 highlight the level of mercury that has been released into the ASGM environment on Lombok. The values reported are a mean concentration across both the Sekotong mining area and the Mataram suburb of Sekarbela. The maximum mercury concentration in each of ore, amalgamation tailings and cyanide tailings exceeds 6600 mg kg^{-1}, with the mean concentration above 1500 mg kg^{-1} for each material. The concentration of greatest concern is that in the cyanide tailings, as this represents the final waste stream from mining that is left in unlined tailings ponds, or discharged directly into rivers or the sea. The mean mercury concentration of this waste was 1628 mg kg^{-1} ranging from 103 to 6615 mg kg^{-1} (63 samples from four locations). Similar to gold, there was no correlation of mercury concentration with depth ($r = 0.0369$) where sampling of cyanide tailings was conducted as a

function of depth. All tailings samples exceeded the maximum permissible concentration for mercury in soil set by the Indonesian Government (20 mg kg^{-1}).

The range of data for the amalgamation tailings indicates variable use of mercury by the artisanal miners. There is no set amount of mercury prescribed for use in grinding, and no defined number of times that grinding will occur. It is likely that rock ground a number of times will have a higher residual mercury concentration.[13] There was no significant correlation of gold concentration with mercury concentration for the amalgamation tailings ($r = 0.2772$).

There is an almost 50% decrease in the concentration of mercury in the cyanidation tailings relative to the input amalgamation tailings. However, given the variability in the data, this result is not significant. For one location (site 3) there was an increase in the mercury concentration of the cyanide tailings relative to the amalgamation tailings. This increase may reflect differential concentrations in the tailings (input and output) over time.

The average mercury concentration of the primary ore was high, although this may be affected by two values significantly above 1000 mg kg^{-1}. These two values may represent contamination of the ore by the workers with mercury through spills or handling. However, a geologically high concentration of mercury in the rock cannot be discounted. The geology agency of Indonesia conducted a survey of the currently exploited mining area in 2006, and reported that some samples contained a high concentration of mercury, although no values were specified.[25] By our assessment there are no published English language mineralogy reports describing the ore processed in the Sekotong and Sekarbela areas.

Sumbawa. Less samples were collected from Sumbawa (three sampling locations), but the results follow those of the sampling on Lombok (Table 3). The mean gold concentration of ore on Sumbawa was very high (955 mg kg^{-1}), however this is distorted by the range of values recorded. The highest gold grade was 4680 mg kg^{-1} (almost 0.5%) and was confirmed through triplicate analysis of the ore sample collected from the corresponding sampling point. This gold grade is similar to that of ore mined by artisanal methods at the Serra Pelada mine in the Brazilian Amazon during the early 1980s,[26] regarded by many as the most infamous ASGM mining operation of recent history. The mean gold grade in amalgamation tailings was still high (6.89 mg kg^{-1}), and was reduced to the same concentration in the cyanidation tailings as reported for Lombok (1.17 mg kg^{-1}).

The average mercury concentration in amalgamation and cyanide tailings collected from Sumbawa was very similar to the concentration recorded from Lombok. The mean, maximum and minimum concentration of mercury recorded in the primary ore was lower than for the Lombok samples. This may reflect a lower mercury concentration in the ore, or less contamination owing to the more recent onset of mining activities (within the past two years). Only three samples were collected from a single cyanidation facility in Sumbawa. This is insufficient data to present meaningful data analysis of the mercury concentration in the cyanide tailings, although the mean value is presented for comparison.

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Methyl mercury in rice

In any consideration of human developmental neurotoxicity, methyl mercury is a species of concern. The physiochemical (reducing) conditions present in a rice paddy environment can facilitate mercury methylation due to the presence of a flora of sulphur-reducing bacteria.[27,28] Therefore, this land-use is of concern where there is an identified point-source discharge of mercury into the environment. Across the ASGM areas of Lombok and Sumbawa, ASGM occurs alongside farming, and the agriculture sector is dominated by rice production. At many locations rice paddies can be seen directly adjacent to amalgamation or cyanidation operations. At several of the visited locations in Sekotong, cyanidation waste is discharged directly into rice paddies which have been informally re-designated as tailings dams. These dams have no system for leachate containment, and therefore soluble complexed mercury, presumably including mercury cyanide, is free to move throughout the environment.

A summary of the methyl mercury concentration recorded in rice plant samples collected from adjacent to two cyanidation tailings dams is presented in Table 4. There is no defined permissible level for methyl mercury in food crops. Guideline values are prescribed for total mercury only. For example, the maximum permissible limit of total mercury in food crops recommended by the Chinese National Standard Agency is 20 ng g^{-1}.[29] There is no safe level of methyl mercury in food. The average methyl mercury concentration reported for rice sampled from ASGM cyanidation facilities in Sekotong exceeds the Chinese mercury guideline level based solely on the methyl mercury concentration. Values reported in Table 4 are similar to those reported by Meng *et al.*[29] and Horvat *et al.*[30] for methyl mercury in rice at the Wanshan mining area in Guizhou province, China, regarded as an area of serious mercury contamination. The recorded methyl mercury values for Sekotong represent a potential threat to the health of local residents, but consumption of this rice is likely restricted to the mining area. The farmers working the rice paddies during sampling stated that rice in the area was used for personal consumption, and not sold outside of the mining area. A control sample of rice obtained from a market in Mataram recorded a methyl mercury concentration of 1.02 ng g^{-1}. This concentration may represent the background level of methyl mercury in non-contaminated rice.

Total and methyl mercury in hair

The concentration of total mercury and methyl mercury in hair for the exposed and control groups defined for this research is

Table 4 Summary of the methyl mercury (Me-Hg) concentration in rice collected from paddy fields adjacent to a cyanidation facility in the Sekotong artisanal mining area

Location[a]	Sample	*n*	Mean ± SD	Max	Min
			Me-Hg concentration ng g^{-1} dry weight		
1	Rice seed	6	57.7 ± 42.9	115	10.6
1	Rice hull	6	28.6 ± 25.3	64.9	4.33
3	Rice leaf	7	36.0 ± 24.9	103	0.63

[a] Locations are those defined on Fig. 1.

presented in Table 5. The age range for the exposed group was a boy of 6 to a 50 year-old male. There were four children of age 16 or younger in the exposed group, although it is not known to what extent these children were actively working. The exposed group was dominated by males (70%). The age range of the control group was similar (boy of 9 to a 50 year-old male), with males comprising 55% of the sample population. The mean total-mercury concentration in hair of the exposed group was significantly elevated relative to the control population ($p < 0.01$). However, there was no significant difference for the mean methyl-mercury concentration in hair between the two groups. There was no correlation of total- or methyl-mercury concentration with age for either the exposed group ($r = 0.0762$, $r = 0.1596$ respectively) or the control group ($r = 0.1323$, $r = 0.2566$ respectively).

Hair is considered a good indicator of elemental mercury exposure and of dietary intake of inorganic and methyl mercury species.[31,32] Hair is more easy to sample, store, transport and analyse than urine or blood, which are the other indicators of mercury exposure to human populations. Total mercury in hair comprises both inorganic mercury and organic mercury. The primary exposure pathway for inorganic mercury is the inhalation of elemental mercury in air, while that for methyl mercury is the ingestion of contaminated food.[33] To differentiate the two exposure pathways in the current dataset, the percentage of total mercury as methyl mercury was calculated (Table 5). The exposed group showed a significantly lower percentage of total mercury as methyl mercury ($p < 0.05$). In combination with the significantly elevated total mercury concentration in hair, this result indicates that the exposed group has suffered significantly higher mercury exposure than the control group, and that exposure has been primarily to volatile elemental mercury in the atmosphere rather than methyl mercury in food.

The hair methyl-mercury concentrations for the control group from the current study are similar to those reported by Li *et al.*[33] for a control group from Wuchan in Guizhou province, China, but the concentrations for the exposed group are nominally lower than those reported for an exposed group at artisanal mercury mines at Wuchan in the same study (2320 ± 1260 ng g^{-1}; range 830 to 5890 ng g^{-1}). The total mercury concentrations for the control group in the current study are higher than those reported for the Chinese study. But the concentrations for the exposed group are lower than the corresponding group in China (69 300 ± 44 400 ng g^{-1}; range 9910 to 143 000 ng g^{-1}). This indicates that the extent of exposure of ASGM miners to mercury in Lombok is lower than in China, but also indicates relatively higher exposure of the general (non-ASGM exposed) population to mercury. The pathway of exposure for the general population is unknown, but could be due to air pollution in Mataram. Total-hair mercury concentrations above the values recorded in Lombok have been reported for the urban population of ten cities in Japan not exposed to ASGM.[34]

Six of the 22 workers from the Li *et al.*[33] exposed group showed clinical signs of mercury poisoning. In the current study there was a greater incidence of headache reported for the exposed group than for the control group, and literature indicates that this could be attributable to mercury poisoning. Further human health studies in Sekotong would verify the accuracy of this hypothesis.

Table 5 Comparison of age, methyl mercury (Me-Hg) and total mercury (T-Hg) concentration, and % of T-Hg as Me-Hg between the control and exposed groups on Lombok Island (Sekotong, Sekarbela and Mataram city)

	The exposed group			The control group		
	n	Mean $\pm$ SD	Range	n	Mean $\pm$ SD	Range
Age	40	28 $\pm$ 8	11–50	40	24 $\pm$ 11	9–47
Me-Hg (ng g^{-1})	21[a]	1004 $\pm$ 605	356–2550	23[a]	755 $\pm$ 383	188–1530
T-Hg (ng g^{-1})[c]	40	7720 $\pm$ 11 610	805–52 500	40	2520 $\pm$ 2330	263–11 600
%Hg as Me-Hg[b]	21	24 $\pm$ 18	0.99–75.13	23	38.00 $\pm$ 17.38	7.77–66.78

[a] Insufficient hair was collected for some participants to allow methyl mercury determination in all samples. [b] Significant difference was observed between the exposed and control groups at $p < 0.05$. [c] Significant difference was observed between the exposed and control groups at $p < 0.01$.

The need for future environmental monitoring and management of ASGM in West Nusa Tenggara province

The data presented in this paper indicate that a detrimental impact is occurring on both the environment and the health of the population in the ASGM mining areas of Lombok and Sumbawa. The increased concentration of total mercury in the hair of the exposed group relative to the control group indicates exposure to volatile inorganic mercury in the air with origin from mining and smelting activities. Future studies to investigate the concentration of gaseous mercury in ambient air will provide data to support the magnitude of this pathway and better assess the extent of more widespread atmospheric mercury pollution in Lombok. In our opinion a major concern in the surveyed ASGM areas is the fate of mercury discharged into the environment with cyanidation tailings. Research in China has shown that rice consumption can be the main pathway of methyl mercury exposure to inhabitants at inland Hg mining areas.[35,36] Levels of methyl mercury recorded in rice growing adjacent to cyanidation tailings indicate that mercury cyanide compounds are moving into the wider environment, methylating, and being accumulated in rice grain. Meng et al.[29] showed that methyl mercury behaves as a mobile nutrient in rice, meaning that methyl mercury accumulated throughout plant tissues during growth is moved to the seed as it ripens. This further increases the risk of exposure of the ASGM communities to methyl mercury. Further environmental monitoring of air, soil, tailings, water and plants is necessary to better define the extent of mercury contamination of all components of the ecosystem. With time, levels of methyl mercury in hair may increase for the exposed group if the magnitude of the food exposure pathway (concentration in rice and amount of rice eaten) increases. Where harvested rice is sold or otherwise exported to outside of the mining area, methyl-mercury contaminated food will increase the level of exposure of the non-mining population to this pollutant.

A largely ignored area of environmental risk at ASGM areas worldwide is the uncontrolled or poorly-managed disposal of waste tailings.[13,37] Many technology projects have focussed on mercury use and have attempted to develop a system where mercury is used more safely, for example retorting, or where the amalgamation process is replaced by alternative technology.[13,22] NGOs such as the Blacksmith Institute in Indonesia are working with communities to reduce volatile mercury concentrations to the atmosphere. However, the issue of tailings disposal in ASGM operations has been less studied, and Veiga et al.[13] identified a need for practical concepts in tailings management. A system whereby miners are encouraged to contain the waste in a properly designed facility could mitigate some of the environmental concerns reported for Lombok and Sumbawa. But there needs to be an economic driver for this to occur. It is unlikely that an artisanal miner will spend money on a waste containment system where no follow on revenue from such infrastructure can be expected, and where no regulations are in place to enforce tailings management.

The cyanidation tailings surveyed in this work contained a gold concentration in excess of 1 mg kg^{-1} and this is a gold grade that could potentially be exploited using alternative gold extraction technologies. One possibility is phytoextraction and phytomining which Tack and Meers[38] and Lottermoser[39] recently described in the context of mine waste rehabilitation. Gold phytoextraction has been proposed by Anderson et al. (2005) as a possible option for tailings management at ASGM locations. In the described scenario, part of the residual gold content of the tailings would be recovered using plants and this could generate revenue from the operation. If appropriate and simple technology could be used to recover residual gold from the tailings, while at the same time stabilising or rehabilitating the waste material, this could represent an economically viable strategy for long-term tailings management that may incentivise environmental protection.

Ongoing research is investigating the suitability of ASGM tailings as a growth substrate for a range of plant species, as successful growth of plants is a key first step in re-vegetation and phytoextraction. However, past research has shown that revegetation of mercury mine waste will promote volatilisation of part of the metal burden into the atmosphere, and this is a consequence of revegetation that must be monitored.[19]

Despite the negative impacts of ASGM, the desired objectives of mining to generate livelihoods, employment and income are positive. However, currently in West Nusa Tenggara province there is no apparent awareness of the danger of the combined mercury and cyanide burden of the tailings, and no apparent safety protocols in place to protect the community from environmental risk. The purpose of the survey described in this paper was not to generate a case in support of the closure of mining, but to establish the level of environment risk such that an appropriate environmental monitoring and management plan can be implemented.

Conclusions

The extent of artisanal and small-scale gold mining is increasing in Indonesia, despite the illegal nature of the activity. Mining has expanded from the traditional areas of Sulawesi and Kalimantan to include West Nusa Tenggara province. Background data on the effect of mining on the environment and on the health of workers and the community is lacking in these new mining areas. The sequential use of whole-ore amalgamation then cyanidation to liberate gold from often very high-grade rock, followed by the discharge of cyanidation tailings into the environment, has resulted in concentrations of mercury in tailings above safe limits. Where cyanidation tailings are discharged into an agricultural environment, levels of methyl mercury in rice above total permissible mercury levels for food have been recorded. Hair samples collected from ASGM workers in the Sekotong and Sekarbela operations show elevated concentrations of total mercury relative to a population not exposed to ASGM activities, but there was no difference in the methyl mercury concentration in hair. Current-day exposure appears to be the inhalation of volatile mercury from the atmosphere rather than the consumption of methyl-mercury-contaminated food, although the relative importance of this second exposure pathway may change in the future as the magnitude of this pathway increases. Initiatives to reduce the flux of mercury into air are ongoing in WNT province, but appropriate technology and ideas are needed in these mining areas to manage the discharged tailings. Phytoextraction may be an option where the waste is contained and planted with appropriate species that are selected based on their growth performance in the tailings. The gold grade of cyanidation tailings in Lombok and Sumbawa is such that gold phytoextraction might be feasible. Any gold revenue in this scenario could pay for the containment and management of the mercury within a simple but effective tailings facility, protecting the environment from uncontrolled mercury release.

Acknowledgements

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