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The identification and testing of a method for mercury-free gold processing for artisanal and small-scale gold miners in Ghana

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Abstract: A study of the ASM sector of Ghana established the practices and attitudes of gold miners and proposed an alternative to mercury amalgamation. The study showed that miners were aware of health hazards associated with mercury but continued to use it because they knew of no credible alternative. It was realised that any process to replace amalgamation must be very efficient to capture gold around 50–100 µm. To be acceptable to the miners the method must be: easy, quick, cheap, transparent and suitable for processing small batches of concentrate. Direct smelting was selected as the technique of choice.

Keywords: small-scale mining; gold; smelting; Ghana; mercury-free processing.

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1 Introduction

Mercury is used by artisanal and small-scale (ASM) gold miners throughout the world, and the pollution caused and the health problems that follow are well-documented (Anon, 1999; Appleton et al., 1999; Drasch et al., 2001). Mercury is used in different ways and at different stages of the mining and gold extraction process, and this varies from country to country and region to region. There have been many projects launched that have attempted to reduce both the overall use of mercury and particularly its release into the environment. It is well established that using retorts can virtually eliminate the release of mercury from the final stages of gold ore processing but projects to introduce them as a best practice in ASM areas have met limited success.

This paper reports findings from a project which sought to:

1 establish the practices and attitudes of miners towards mercury use

2 investigate the possibilities of identifying a processing method that can actually be a substitute for the use of mercury in the ASM sector in Ghana

3 test the identified process, first in the laboratory and then in the field in a local mining area

4 if successful, disseminate the information to the wider ASM community in Ghana.

During the first phase of this project, the ASM sector in Ghana was assessed, drawing upon past reports and the extensive knowledge of the project team, supplemented by a Characterisation Survey carried out in the main mining areas. This established a clear picture of the mining and processing methods and the way mercury is used in Ghana. A review of existing literature and personal experience of the authors were used to identify the process or processes that have the most potential as a substitute for mercury and a programme of laboratory and field testing was proposed. This paper is a précis of a comprehensive report of the first phase of the project (Styles et al., 2006a). The laboratory testing phase of the project is the subject of a second report (Styles et al., 2006b) and is summarised in the accompanying paper by Amankwah et al. (2009). The study was made possible through the EU Mining Sector Support Programme in Ghana.

2 The use of mercury by artisanal gold miners and technology transfer

Previous studies, particularly in South America, have shown that mercury can be used at various stages of the mining and gold recovery process. This includes mining, where mercury is thrown in to the pit to collect fine gold; milling, where it is put in the ball mills; and sluicing, where it is put in the sluice box to collect small particles together to make them easier to capture. These processes are all highly damaging to the environment as mercury is easily lost, but worse still, demonstrably inefficient practices, as far greater benefit can be gained by using good standard practice. Luckily, these practices appear to be rare in Ghana. Disc mills rather than ball mills are used for fine milling. This is not amenable to mercury use; moreover, mercury use in sluices appears to be rare.

The main stage where mercury is used is the recovery of small gold grains from the black sand concentrates collected on sluices. This process is widespread and very effective, and most miners know of no alternative method. The procedure consists of adding mercury to the black sand in the pan and rolling and rubbing it through the sand so that it gets in contact with the gold grains and sticks them together to form a gold mercury amalgam paste. The black sand with the gold removed can subsequently be washed away, leaving only the amalgam. The amalgam can then be heated over a fire or with a blowtorch to drive off the mercury as vapour, leaving behind yellowish-brown sponge gold. This is a serious immediate hazard to the operators and a long-term hazard to the local area. This heating process would ideally be carried out in a retort with the mercury vapour condensed, captured and reused.

Several projects have previously been carried out in Ghana connected with the reduction in the use of mercury, the most significant of which was the UNIDO mercury project (Babut et al., 2003). Although retorts had been made available under the project and were present at several processing sites, there was no evidence that they were being used by artisanal miners. The retorts are too difficult, slow and cumbersome to use, taking perhaps 2 h to process a ball of amalgam compared to 5 min with a fire or torch (Hilson and Pardie, 2006; Hilson et al., 2007; Tschakert and Singha, 2007). There is considerable difficulty making and maintaining a heat source that is sufficiently hot for the retort to work efficiently. The miners refuse to wait that long to get the end result of their labours.

It is important to understand why the impact of these projects has been so limited: Is it that the technology was inappropriate or that the methods employed to introduce the technology were ineffective? The outcome of various projects were analysed and the response of miners were studied. It may be clear to an outsider that inefficient or hazardous methods are being used but if that is what they all do, it could be seen as 'normal'. For any new method to be accepted it must be simple and cheap, using locally available materials not expensive imported equipment and must show direct financial benefits in the short term (Hinton et al., 2003). Long-term health benefits from a process such as retorting have previously been clearly explained and demonstrated.

The glass retort introduced is fragile and not good for use in the rugged small-scale gold mining environment and the bad heat conduction of glass slows production. The technology that is effective in an ideal environment is not appropriate in the ASM setting. Past projects have shown that it is a non-starter. It is clearly vital that the technology must not just be effective but also appropriate. Once an appropriate technique is identified and tested, demonstrations are a necessary and effective method of communicating the new technology, particularly if the larger, more important sites in an area are used and the successful, influential miners are 'buying in' to the process. Miners tend to copy their neighbours if they think they have something better. Demonstrations must be a part of any programme.

3 Characterisation survey

A clear picture of the ASM practices and the attitudes of operators is an important starting point for the selection of a possible method to replace the use of mercury. To achieve this, a national Characterisation Survey was carried out. The Survey covered a wide range of factual information, including the geology of the mining area and the types of deposit being worked, the size and organisation of the mining site, the mining and processing techniques used and the legal status of the operation. It was necessary to know the nature of the gold-bearing ore, particularly the grain size of the gold, as this determines the possibilities and options for gold recovery. This information was needed to understand why and what the miners do and the technical problems and difficulties miners face. In addition, it was necessary to know if the miners used mercury and at what stages of the mining or processing it was used. If they used mercury, were they aware of the hazards and did they know of any alternative? Finally, it was essential to know what the miners' attitude was to using an alternative to mercury and what were the vital features of any alternative method to make it successful, and particularly, the economic factors including the process of selling gold to dealers. The Survey was based on a questionnaire implemented by graduate students from University of Mines and Technology (UMaT), Ghana, and supplemented by observations made by the members of the research team.

3.1 Mining methods

Ghana's artisanal and small-scale miners process two major categories of gold ores: alluvial/eluvial and hard rocks. The hard rock, which may be lode or reefs, could be free milling or refractory ores. Subsequent studies of the data showed that the type of ore and mining method have a major influence on all subsequent processes and hence will be described separately.

3.1.1 Alluvial mining

Alluvial mining generally involves digging pits ranging from less that 2 m in depth in the gravel beds of small and slow moving streams, or in eddying pools on the shallow banks of larger rivers to large pits possibly 10–20 m deep and 100 or more metres across. The smaller pits are operated by artisans or *galamsey*.

Another mining technique for alluvial/eluvial deposits used by *galamsey* involves the digging small circular pits or shafts by individuals. Larger excavations may go down to 20 m deep and over until the gravel horizon is located. The ore excavated from these pits is usually carried in head pans to suitable locations for processing either by sluicing or panning. In some places, work is organised in 'family' groups with the men digging the ore and the women doing the sluicing and panning, while in others women only carry the ore from the pits to the processing site. These sites are often unlicensed and poorly organised with little regard for health and safety and environmental consequences.

3.1.2 Hard rock mining

Primary hard rock underground operations feature narrow, vertical/inclined shafts or adits for access to the ore body. Shafts range in size (1–2 m in diameter if circular or 1 m × 1–2 m for square and rectangular shafts) and depth (10–50 m), and occur in a variety of shapes, ranging from chimney type, to long 'snakelike' tubes that bend to follow the line of the reef.

They deploy a variety of tools (shovels, picks, hammers, axes, chisels, metal bars, mattocks, etc.) to loosen and excavate the ore, especially when in the form of weathered quartz veins. The ore is shovelled into sacks and buckets and transported to the shaft. In some cases where miners encounter very hard rock, explosives are used, though this is illegal (Aryee et al., 2003).

In general, there is little regard for proper health and safety procedures, and underground mining in particular is a dangerous and hazardous activity. Ventilation is often a problem in the deeper mines, particularly after blasting, and various kinds of pumps are used in some places. Since miners face daily and immediate danger of rock falls that kill or maim instantly, mercury that poses long term hazard from a slow cumulative poison may seem a comparatively small risk.

3.2 Ore processing

After mining, the ore is processed to liberate and separate gold grains. For alluvial ores, liberation is accomplished by scrubbing and washing, while comminution is used for hard rock. Primary separation is generally conducted in sluice boards and the sluice concentrate is cleaned in pans before amalgamation. Small-scale miners extract only gravity recoverable gold and overall recoveries are estimated to be between 30% and 40%. The finer gold particles in the tailings that require dissolution for recovery may be processed profitably by larger companies.

In many ASM regions, the processing sites are separate from the mining areas and closer to sources of water and power. Some sites act as independent central processing centres that provide a service and treat ore from many sites in their vicinity. The ore is either transported using rented/hired trucks or hand carts, and if within a reasonable distance, carried in sacks.

3.2.1 Washing and screening

The main pre-concentration processes performed on alluvial material are washing and screening. Washing is carried out mainly on alluvial gold ores to remove pebbles, break up clay and remove slimes. The extent and mode of washing usually depends on how strongly the clay adheres to the surface of the gold. If the clay content is low and adhesion to the mineral surface is weak, washing and screening are done simultaneously, usually by shaking a hand held screen (with the material in it) in water. On more mechanised sites (e.g., *Kodkoff Mining Services Company* at the Kobirsu site in the Akyem Oda area), the scrubbing is undertaken using specific mechanical scrubbers and the loosened material screened through trommels. Some miners carry this out in rotating drums used locally for mixing concrete. Other miners perform this operation by pounding and shearing the material with their feet in basins after pre-soaking with water. In both cases, the added water is decanted from time to time and fresh water is introduced. The process continues until the gravel and sands are relatively clean.

Screens used in gold processing are usually selected on the basis of gold particle size in the area under consideration (with ‘nuggety’ areas using screens with larger openings). However, most Ghanaian miners often do not have a choice of screen size and are forced to use whatever is available. Most miners use metal woven screens for coarse separation and rayon-type material for fine screening. Constant abrasion from the ore usually causes an increase in the openings of the rayon material and as a result has to be replaced frequently.

3.2.2 Comminution

Liberation from hard rock ores begins with comminution. Currently, size reduction is conducted using hammer and disc mills. Though hammer mills are generally used for primary crushing, some are coupled directly to sluice boards. For secondary milling, disc mills used locally for grinding corn and other foodstuffs have been modified and equipped with harder grinding surfaces for pulverising the hard abrasive ores. In most processing centres, such units may only work for part of the day unless there is sufficient ore available for continuous operation. These mills break down and require repairs on a very frequent basis.

There are extremely high levels of airborne dust at the centralised processing plants as this grinding is invariably dry. In many cases, the comminution is carried out inside huts or buildings with no forced ventilation to remove the dust. In such places, the workers are exposed to dangerous levels of siliceous dust and high noise levels but are rarely provided with suitable Personal Protection Equipment (PPE), dust masks or ear plugs.

3.2.3 Concentration

In Ghana, there are number of gravity concentration units that are now available to the formal ASM sector, including sluices and shaking tables, jigs, gold savers and centrifugal concentrators (such as the *Knelson* Concentrator that is available from mining equipment suppliers). However, by far, the most common unit in use, especially by the *galamsey*, is the standard sluice box (or board). These units are relatively cheap, easy to use, and are well suited to the mining environment of Ghana. The sluice boxes are all built locally using hard wood boards or metal sheets (with sides slightly curved inwards) or even split bamboo. The board is lined with either a basic blanket, towel, carpet or jute material, but increasingly 'miner's moss', astro turf or *Nomad*® type matting is used where it is available.

Most sluices seen during the survey only had one type of lining, that is not applicable to all particle sizes. Although most sluices are very crude, some are more sophisticated and use riffles and de-sliming units. At most sites, the sluiced tailings are scavenged several times before they are finally discarded to increase retrieval of gold particles lost in previous operations. There is a lot of scope for improving the design of the sluice boxes used.

After the first separation operation such as sluicing, concentrates consisting of black sands with a small percentage of gold are produced. These are generally cleaned by hand panning in wooden or rubber pans (cut from rubber sheets). This panning produces a gold-rich concentrate but this still contains a lot of black sand, perhaps 75%. Separating the gold from this concentrate is easy if the gold is coarse but a major problem when it is very fine grained. In most places, miners use mercury amalgamation to separate the gold from the black sands.

3.3 Testing of gold ores

There was virtually no information available about the grain size of gold ores from the ASM mining regions in Ghana. It is, however, vital to know this to be able to select a suitable method for gold recovery; a small programme of gold grain size measurement, therefore, was carried out.

Samples of gold concentrate were collected from mine sites throughout Ghana to establish a baseline of gold grain size data. Eighteen samples were analysed using the method of sieving and grain size counting (Styles et al., 2002). The measurements showed, as might be expected, that there were clear differences between alluvial and hard rock ores.

The sample from the Bonte area, where there is small-scale and artisanal mining, is a good example alluvial ore. As Figure 1 shows, 80% of the gold is in the form of particles coarser than 0.25 mm and 40% greater than 1 mm. This means that most of the gold is easily separated from black sand by careful panning or simple methods such as 'blow and tap'. In contrast, the hardrock ores show a significant difference; the gold from the processing plant in Tarkwa (Figure 2) had a predominance of smaller grains, 30% of which was coarser than 0.25 mm (easily recoverable) but 50% less than 0.125 mm and thus difficult to recover. The gold from a processing plant at Bolgatanga (Figure 3) shows an even more extreme size distribution, with less than 10% coarser than 0.25 mm and more than 80% smaller than 0.125 mm, and very difficult to recover.

It is easy to see why the miners resort to mercury to recover gold in these hard rock mining areas.

Figure 1 Grain size distribution of gold from alluvial gravel in the Bonte area

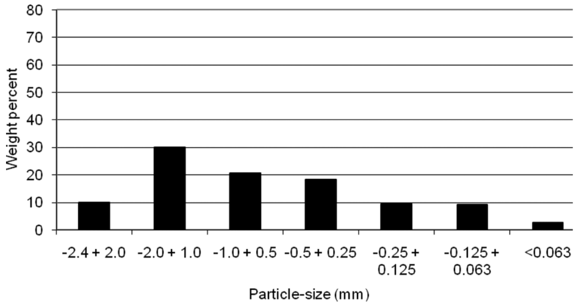


Figure 2 Grain size distribution of gold from hard rock ore from the Tarkwa area

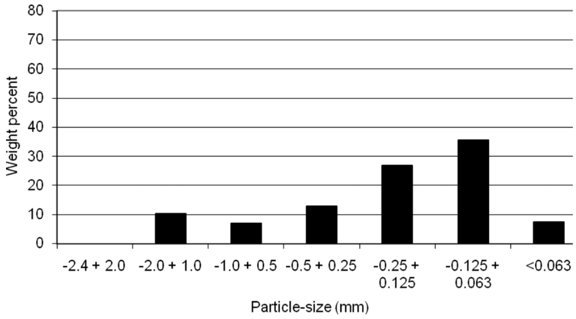
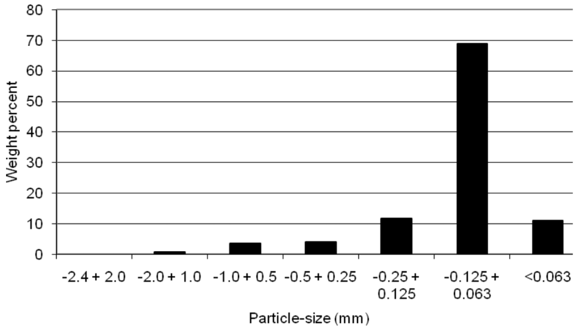


Figure 3 Grain size distribution of gold from hard rock ore from the Bolgatanga area



The testing of gold ores established the most important parameter: that any alternative method must be very effective for gold less than 100 microns in size.

3.4 Attitudes to change

The Characterisation Survey investigated miners' knowledge and attitudes towards mercury and the desire or willingness to adopt alternatives. In most places, people generally seemed to know that mercury was not particularly good for them, but knew very little about the specific problems and probably do not really understand how a cumulative poison acts. Few, if any, knew of anyone who had been seriously affected by mercury poisoning, and this probably accounts for their general lack of concern about its widespread use. Most said they would be happy to use an alternative if it was as effective as mercury amalgamation.

Various other social factors were examined as part of the Survey but these do not appear to have a major influence on the use of mercury or the willingness to change. Health concerns are a very low priority for the groups studied. Speed, cost and efficiency are the overriding factors. Any process that cannot match amalgamation on these criteria has little chance of acceptance.

4 Alternative methods

In Ghana, mercury is principally used for the separation of small gold grains from heavy mineral concentrates. From the results of the survey it is clear that mercury is widely used because it is:

- Effective
- Easy to carry out (requires no special equipment)
- Quick
- Inexpensive
- Suitable for processing small batches of concentrate
- Visible (the miners can see their products throughout the whole process).

A desk study was carried out to assess various processing methods that are currently available for the separation of gold. The guidelines outlined above were important but the vital criterion was that it must be very effective for gold grains smaller than 100 microns. Table 1 shows the various methods and their applicability in small-scale mining.

Table 1 Matrix showing processing methods and their application in small-scale operations

Method	*Equipment/ process*	*Principle*	*Comments*
Physical	Sluice	Gravity concentration leading to production of a rough concentrate that has to be cleaned further	Used in virtually all small-scale mining centres as a conventional rougher concentration unit
	Cleangold sluice	Gravity concentration leading to production of a clean concentrate	Trials showed that it did not work well for the hard rock ores as the high magnetite content clogged the sluice very quickly and a good separation could not be achieved. It was also not suitable for coarse particles as there were too big to be trapped in the magnetic riffles. It was not considered as a viable method for the types of ores encountered

Table 1 Matrix showing processing methods and their application in small-scale operations (continued)

Method	*Equipment/ process*	*Principle*	*Comments*
Physical	Shaking table	Gravity concentration leading to production of a clean concentrate	Good shaking tables are expensive to make and the level of control is difficult to achieve in the ASM environment. They do, however, have potential as a first stage concentration device at processing centres to remove most of the black sand. Relatively large volumes can be processed compared to hand panning but it is still likely that a final finishing technique will be required to produce a clean final product
	Centrifugal concentrators	Gravity concentration leading to production of a clean concentrate	Centrifugal concentrators handle fine gold particles down to 30 µm and below. These machines have the capability to carry out the required separation but they are expensive costing many thousands of dollars, they could have a place at large processing centres but are way beyond the reach of small artisanal groups
Physico-chemical	Coal-Gold Agglomeration	Agglomeration of fine gold particles and coal, followed by flotation with diesel, kerosine and other oils. The float concentrate has to be processed and smelted	The process has been tested in Australia, South Africa, Brazil and Tanzania. It appears that despite its apparent attractions it was never actually put in to operation and more research is required. Ghana does not mine coal and its importation could be an added cost but alternative carbon sources such as carbonised palm kernels or coconut shells might be useable
Chemical	IGoli® process	Leaching with HCl and NaOCl followed by filtration and precipitation with sodium metabisulphite. The slimes precipitated are calcined and smelted	The process has been applied in South Africa and Tanzania. Due to the safety hazards involved in working with acids and the miners' lack of training in chemistry, Mintek insists on miners attending a training course. They stipulate that at least one miner must be trained by Mintek at their laboratories in South Africa so that he can take the technology back and train other miners. The training course includes practical test work, a visit to a small operating mine, engineering design drawings for the manufacture of the strakes and a simple booklet giving details of the process. For many ASM experts the iGoli® process, still needs more research and field test work prior to being justly promoted as a viable alternative and is currently more suited to organised medium scale, rather than artisanal and small-scale mining operations

Table 1 Matrix showing processing methods and their application in small-scale operations (continued)

Method	*Equipment/ process*	*Principle*	*Comments*
Chemical	Cyanidation	Leaching with sodium cyanide and oxygen followed by adsorption onto activated carbon, elution electrowinning and smelting concentrated solution that requires further processing	Cyanidation has been applied by small-scale miners in Colombia, Bolivia, Brazil and Zimbabwe. For small-scale operators, activated carbon adsorption may be suitable as the loaded carbon may be assayed and sold to a large-scale gold mine or gold dealer for further processing as is done in Brazil. Gold lixiviation using cyanide is not allowed in Ghana, mainly due to the acute toxicity of sodium cyanide and the relatively low environmental consciousness of the average miner. The method is not fast enough for processing concentrates as it takes a long time. However, it could have an important role in the treatment of tailings from processing centres, but as it is illegal and these tailings are not currently treated with mercury this falls outside the scope of this project
	Haber	Leaching with a concentrated solution that requires further processing	The leaching reagent is proprietary. For this process artisanal miners have to take their ore to processing centres where it is processed. First a sample of ore is tested and the ore purchased, the small individual batches are mixed together to produce a load suitable for processing and the miners are paid by the company after processing. We suggest that this is not applicable to the artisanal environment as it is 1 too costly and too complex for individuals or small groups 2 uses a proprietary chemical, thus locking the miners into a foreign third party supplier 3 has major issues of trust and keeping track of an individual's ore
	Smelting	Melting black sand concentrates to produce pure gold	Smelting is applied in most small scale centres and miners are familiar with the method as it is currently applied for purifying sponge gold. It has, however, not been applied in processing of concentrates and needs development and testing.

From Table 1, it can be seen that sophisticated physical methods are too expensive and hence a chemical method is required. Smelting is the only chemical process that is not based on dissolution. More importantly, it is the only process that produces pure gold in a single step, as the gold along with some black sand, obtained after winnowing, panning or tabling may be smelted to obtain purer metal in a single mass. It has theoretical potential.

4.1 Overview from the desk study and characterisation survey

The Characterisation Survey has determined that most mercury is utilised after secondary gravity concentration. Mercury amalgamation is both cheap and effective, and miners have little incentive to seek an alternative. An important baseline is actually testing the efficiency of amalgamation, as it is widely believed by miners to be highly effective; but there is little actual testing to support this. The challenge was to identify and test an alternative that can separate fine-grained gold from heavy mineral concentrates effectively.

The various gold processing techniques outlined in Table 1 were compared with amalgamation. A summary of the advantages and disadvantages of the various processes evaluated is shown in a matrix of benefits (Table 2). The methods are rated from 1 to 3, where 1 is 'poor' and 3 is 'good'.

Table 2 Matrix of benefits of processing methods

Method	*Speed*	*Cost*	*Visibility*	*Batch processing*	*Simple operation*	*Toxic hazard*	*Effective for small gold grains*	*Well developed technology*	*Clean end product*
Amalgamation	3	3	3	3	3	1	3	3	3
Sluice	3	3	3	3	3	3	2	3	1
Shaking table	3	2	3	3	2	3	3	3	2
Centrifugal	3	1	1	3	2	3	3	3	3
Cyanidation	1	2	1	3	1	1	3	3	3
Igoli	2	1	2	3	1	2	3	2	3
Haber	2	1	2	3	1	2	3	1	3
Coal agglomeration	2	3	2	3	2	2	3?	1	3
Direct smelting	3	3	3	3	3	3?	3	1	3

If it can be proved that the method chosen is less hazardous than mercury, there is no loss of gold and that the time taken is comparable, perhaps the miners may be willing to try it. Direct smelting has the best theoretical features though the method is not fully developed. Smelting is used by gold buyers to process the sponge gold that they buy from the miners and hence it is technology that miners know and trust and therefore has some chance of acceptance.

Smelting may be carried out in crucibles and after adding fluxes to the concentrate; the charge is heated to above 1200°C on charcoal, liquefied petroleum gas or palm kernel shell fired stoves. The main types of flux utilised include sodium tetraborate (borax), potassium nitrate, sodium carbonate and silica sand. The ratios utilised depend on the type of material to be smelted. It is simple cheap technology. The method can use relatively small crucibles so is suitable for small batches of ore, which satisfies concerns about visibility and traceability. Work undertaken by Amankwah and Buah (1998) shows that this method is more cost-effective than amalgamation followed by retorting, and it also produces a purer end product. In addition, coated and fine floury gold that is not easily captured during amalgamation or may be lost in the process of 'squeezing out' excess mercury may be captured in the bullion produced.

This method has considerable potential and can fulfil all the criteria as a substitute for amalgamation. Although it requires further development, much like some of the chemical methods described previously, it has the advantage of using inexpensive easily available materials. Moreover, the starting knowledge lay with members of the research team at Tarkwa, which makes further development during the life of the project feasible. Expertise will remain in-country with the Tarkwa staff and not just with foreign consultants that disappear at the end of the project. This has great benefits for on-going development, implementation and sustainability.

5 Strategy for development

It was agreed that direct smelting should be the method selected for testing and development. A programme of laboratory tests was implemented and carried out to fully examine the method in terms of efficiency, limits on the purity of concentrate that can be processed, and efficiency of different fluxes. The aims of the development and test work were as follows:

1. To make sure that it works and is effective. Test works were to be conducted to develop a suitable flux composition for the two major types of concentrates that small-scale miners encounter (sulphidic and non-sulphidic).
2. To show that it is as fast as amalgamation, and measure the time required for each process. For a given weight of sample, measure the time taken for a small-scale operator to go through:
    - a amalgamation
    - b separation of amalgam from black sands
    - c squeezing of excess mercury
    - d heating the amalgam in the open air
    - e smelting and weighing of the sponge gold.

    This will then be compared with the drying and smelting of a similar weight of concentrate.
3. To show that it is efficient, and quantify recoveries for each process. This can be done by buying a known weight of gold after it has gone through amalgamation, heating and smelting. This can then be put back into the black sands and smelted. If either the weight or purity of gold obtained from direct smelting is higher, the miners may be convinced. However, this should be done several times so there is no doubt that the method is reliable.

6 Conclusions

The Characterisation Survey showed that in Ghana, the ASM gold miners can be considered as two separate groups: alluvial miners and hard rock miners. The former excavate gold-bearing gravel and sand that is only loosely consolidated. This gold can be liberated by washing/scrubbing; is relatively coarse – mostly greater than 250 µm; and is captured in sluice boxes or by hand panning. This coarse gold is relatively easy to separate from the heavy concentrate by hand picking or the 'blow and tap' method. The miners, in many places, do not use mercury.

The second group is the hard rock miners, who work gold-bearing quartz veins and have to crush it to a very fine powder, as most of the gold grains are very small, less than 100 µm. They process the crushed ore with sluice boxes and gold is extracted from the heavy concentrates by amalgamation. The amalgam produced is heated in open fires or with blowlamps at the mining site and the mercury vapour released is a major hazard. This group clearly need an effective alternative to amalgamation but as the gold is fine-grained, this is a difficult problem to solve.

A range of possible methods were evaluated and the direct smelting process appears to have a good chance of meeting these demands and was chosen for further development and testing. The results of the second phase of the project are given by Amankwah et al. (2009).

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References

Amankwah, R.K. and Buah, W.K. (1998) 'Some metallurgical aspects of small-scale mining in Ghana', *Proceedings of the Extraction Metallurgy Africa'98 Conference, South African Institute of Mining and Metallurgy*, Johannesburg, pp.1–4.

Amankwah, R.K., Styles, M.T., Nartey, R.S. and Al-Hassan, S. (2010) 'The application of direct smelting of gold concentrates as an alternative to mercury amalgamation in small-scale gold mining operations in Ghana', *Int. J. Environment and Pollution*, Vol. 41, Nos. 3–4, pp.304–315.

Anon (1999) *Assistance in Assessing and Reducing Mercury Pollution Emanating from Artisanal Gold Mining in Ghana – Phase I*, www.natural-resources.org/minerals/CD/docs/unido/sub2igoatt6part2.pdf

Appleton, J.D., Williams, T.M., Breward, N., Apostol, A., Miguel, J. and Miranda, C. (1999) 'Mercury contamination associated with artisanal gold mining on the island of Mindanao, the Philippines', *The Science of the Total Environment*, Vol. 228, Nos. 2–3, pp.95–109.

Aryee, B.N.A., Ntibery, B.K. and Evans Atorkui, E. (2003) 'Trends in the small-scale mining of precious minerals in Ghana: a perspective on its environmental impact', *Journal of Cleaner Production*, Vol. 11, pp.131–140.

Babut, M., Sekyi, R., Rambaud, A., Potin-Gautier, M., Tellier, S., Bannerman, W. and Beinhoff, C. (2003) 'Improving the environmental management of small-scale gold mining in Ghana: a case study of Dumasi', *Journal of Cleaner Production*, Vol. 11, pp.215–221.

Drasch, G., Böse-O'Reilly, S., Beinhoff, C., Roider, G. and Maydl, S. (2001) 'The Mt. Diwata study on the Philippines 1999 – assessing mercury intoxication of the population by small-scale gold mining', *The Science of the Total Environment*, Vol. 267, Nos. 1–3, pp.151–168.

Hilson, G. and Pardie, S. (2006) 'Mercury: An agent of poverty in Ghana's small-scale gold-mining sector?', *Resources Policy*, Vol. 31, pp.106–116.

Hilson,G., Christopher, J., Hilson, C.J. and Pardie, S. (2007) 'Improving awareness of mercury pollution in small-scale gold mining communities: challenges and ways forward in rural Ghana', *Environmental Research*, Vol. 103, pp.275–287.

Hinton, J.J., Veiga, M.M. and Veiga, T.C. (2003) 'Clean artisanal gold mining: A Utopian approach?', *Journal of Cleaner Production*, Vol. 11, pp.99–115.

Styles, M.T., Dsouza, K.P.C., Al-Hassan, S., Amankwah, R., Nartey, R.S. and Mutagwaba, W. (2006a) *Ghana Mining Sector Support Programme Project ACP GH 027, Mercury Abatement Phase 1 Report*, British Geological Survey Internal Report, CR/06/076, p.149.

Styles, M.T., Dsouza, K.P.C., Al-Hassan, S., Amankwah, R., Nartey, R.S. and Mutagwaba, W. (2006b) *Ghana Mining Sector Support Programme Project ACP GH 027, Mercury Abatement Phase 2 Report*, British Geological Survey Internal Report, CR/06/199, p.43.

Styles, M.T., Simpson, J. and Steadman, E.J. (2002) *Good Practice in the Design and Use of Large Sluice Boxes*, British Geological Survey Internal Report, CR/02/029N, p.39.

Tschakert, P. and Singha, K. (2007) 'Contaminated identities: mercury and marginalization in Ghana's artisanal mining sector', *Geoforum*, Vol. 38, pp.1304–1321.