How efficient are they really? A simple testing method of small-scale gold miners’ gravity separation systems

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A B S T R A C T
This paper demonstrates a simple, minimally-invasive method of estimating the gold recovery rate of gravitational separation equipment used by artisanal and small-scale miners at alluvial gold sites in the Guianas, South America. A local ASM group mining an alluvial gold deposit agreed to allow the research team to collect eight samples of ore material immediately before it was to be processed by their sluice and eight samples immediately upon exit from their sluice. Each sample was sieved into three grain size portions (<75 μm, 75–500 μm, >500 μm) and each portion assayed for gold content. The results indicate that the sluice at this site is capturing approximately 91% of the gold that enters the sluicing system, and the grain size distribution of the gold particles suggests that mercury amalgamation methods employed by the miners post sluicing are likely to be very efficient as well. Although this study and sample size is extremely small, and should not be taken as a full replacement of more elaborate geologic sampling and metallurgical analysis, this method could provide a useful tool for practitioners who want to quickly evaluate ASM gold processing methods and consider the effectiveness of introducing alternative processing technologies, especially those that aim to reduce mercury emissions from ASM.

1. Introduction
Artisanal and small-scale mining (ASM) employs approximately 50 million people worldwide and produces 15–20% of the world’s non-fuel mineral resources (Veiga and Baker, 2004). The sector is widely credited with supplying an important livelihood to people in developing countries that suffer from high rates of rural underemployment (Hentschel et al., 2002). Unfortunately, the economic benefits of ASM are accompanied by environmental damage, occupational health and safety problems and in some cases, human rights violations. Large-scale mining companies, governments, non-governmental organizations (NGOs) and scholars recognize the importance of ASM to developing economies, but find the sector unyielding when it comes to curtail the dangers and sometimes illegal activities associated with ASM (Buxton, 2013; Hentschel et al., 2002; Smith et al., 2016).

Although ASM is increasingly active in a wide variety of geologic settings, simple, easy to mine alluvial deposits probably still dominate the ASM sector’s worldwide gold production. Alluvial deposits were almost certainly where gold was first discovered and dominated early history’s production (MacDonald, 1983), and alluvial gold mining technologies have been well understood for centuries. Although relatively simple to find and recover, valuing alluvial gold deposits and testing the efficiency of alluvial mining technologies has been a more complicated matter.

This paper demonstrates a simple, minimally-invasive method of estimating the gold recovery rate of gravitational separation equipment used by ASM at alluvial gold sites in the Guianas. To accomplish this goal, a local ASM group, mining an alluvial gold deposit, agreed to allow the research team to collect eight samples of ore material immediately before it was to be processed by their sluice and eight samples immediately upon exit from their sluice. Each sample was sieved into three grain size portions (<75 μm, 75–500 μm, >500 μm), and each portion was assayed for gold content. The results indicate that the sluice at this site is capturing approximately 91% of the gold that enters the sluicing system, and the grain size distribution of the gold particles suggests that mercury amalgamation methods employed by the miners are likely to be very efficient as well. This method could provide a useful tool for practitioners who want to quickly evaluate ASM gold processing methods and consider the effectiveness of introducing alternative processing technologies, especially those that aim to reduce mercury emissions from ASM.

The Guianas include the South American countries of Guyana, Suriname, and French Guiana; the latter being an overseas department of France.

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alternative processing technologies, especially those that aim to reduce mercury emissions in ASM.

2. Alluvial gold deposits

Gold in alluvial deposits commonly occurs in large, often visible nuggets and in unconsolidated material (MacDonald, 1983; Youngson and Craw, 1995). This condition makes alluvial gold relatively easy to find and recover using simple, inexpensive technology. Miners usually do not have to break or blast hard rock, nor do they have to tunnel or remove substantial amounts of overburden in order to access gold-bearing material. Alluvial gold often occurs as "free gold," or gold that is not chemically or physically bonded with other materials, so prospectors and miners do not have to employ sophisticated milling and roasting processes in order to liberate the gold from gangue minerals and achieve profitable recoveries. Early alluvial miners developed few formal methods of valuing deposits or testing the efficiency of their recovery methods because the capital investments required to mine and the resultant costs of inefficiencies were so low (MacDonald, 1983, pp. 1–12).

Alluvial gold mining began to change in the late 1800s, an evolution that continued until the outbreak of World War II. Large-scale miners in North America and Southeast Asia began to invest in increasingly mechanized mining methods to exploit alluvial deposits, culminating with large-scale dredging systems in the early 1900s (Garnett, 1991; Isenberg, 2005). This level of investment soon required more rigorous deposit valuation systems to justify the investment and mobilization of large machinery. Miners in this period assessed their gold deposits using an "R/E factor" where R is the amount of actual gold recovered from mining a portion of the deposit and E is the amount of gold they predicted they would be able to recover based on pre-mining sampling. An R/E value of 1.00 indicates that the miners recovered exactly the same amount of gold as pre-mining studies predicted (Garnett, 1991).

Geologists estimate the quantity of recoverable gold in an alluvial deposit (the 'E') by taking bulk samples at a fixed spacing. Because the grades of alluvial gold deposits tend to vary widely over short distances, it is difficult to estimate with certainty the true value of a deposit without prohibitively high quantities of tightly spaced bulk samples. Although advances in the application of geostatistical methods, such as Kriging, improved deposit valuation in the late 1900s, alluvial gold deposits often contain small zones of exceptionally high grade – meaning that regular sampling methods often fail to capture values from the highest-grade portions of the deposit. This deposit variability phenomenon and the resulting geostatistical challenge is commonly known as the "nugget effect" (Davis, 1987; Garnett, 1991).

By examining dredging records from the height of North America's alluvial mining period in the early 1900s, it becomes clear how unreliable estimating gold grades and the challenges of the "nugget effect" are in practice. Long-term (multi-year) R/E values ranged from 0.50 to 2.90; a chilling indication of the unreliability of geologic sampling and deposit modeling techniques of the time (Garnett, 1991). As a result of the investment uncertainty and a souring gold market, large-scale mining companies all but abandoned alluvial deposits after World War II, choosing instead to invest in exploring and developing larger, more predictable gold deposit systems (Garnett, 1991). As a result, very little published work on improving alluvial deposit estimation has been conducted since.

Although large-scale companies have been out of the alluvial gold game for decades, the relatively low costs associated with prospecting for, and recovering gold from, alluvial systems is not lost on ASM. While alluvial gold production declined throughout the developed world, ASM gold production began to increase throughout Africa, Asia, and Latin America as government reforms and World Bank-driven economic restructuring liberalized developing economies and gave rural individuals access to the rising gold price (Banchirigah, 2006). In rural gold-bearing parts of the developing world, small-scale mining quickly became an attractive occupation.

Artisanal and small-scale miners' success at exploiting alluvial gold deposits in the 1980s and 1990s quickly led to increased investment in ASM projects from successful miners and local investors, often outside of the formal mining sector (Banchirigah, 2006; Hilson and McQuilken, 2014). Scholars now report that the "small-scale" mining sector is increasingly large, employing relatively expensive and highly mechanized mining and processing techniques which enable them to exploit larger, more geologically complex, and lower-grade deposits (Hilson and McQuilken, 2014; Teschner, 2012, 2014; Verbrugge, 2014; Verbrugge and Besmanos, 2016).

3. ASM gold processing and quixotic western interventions

The ore processing methods used in ASM systems are generally considered to be inefficient and pose serious risks to the environment and human health (Hentschel et al., 2002; Smith et al., 2016). Mercury is often used in ASM gold processing to bind with gold particles to form an amalgam. The creation of this amalgam is a useful method of separating gold particles from other heavy gangue minerals, which fail to bond with the mercury. The gold-mercury amalgam is heated to burn off the mercury, leaving the gold behind in a relatively pure form that is easy to value and sell (Hilson, 2006; Veiga and Baker, 2004). During the burning process, miners often inhale the mercury vapors, exposing them and others in the mining communities to grave health risks. Mercury is a potent toxin that interferes with brain and neurological function; it is particularly harmful to babies and young children (Poulin and Pruss-Ustun, 2008).

Artisanal and small-scale mining is the largest source of anthropogenic mercury emissions worldwide (United Nations Environmental Program, 2013). The United Nations Environmental Program (UNEP) estimates that the ASM sector consumes 640–1350 metric tons of mercury a year – roughly one third of the total global consumption (United Nations Environmental Program, 2008). Unlike other industrial uses of mercury, nearly all of what is used by ASM ends up in the environment. Approximately 40% is released into the air, while most of the remaining 60% is lost into waterways and soil (Telmer and Viega, 2009). Because mercury can travel globally, mercury released by ASM often ends up polluting air, water, and fish all around the world (United Nations Institute for Training and Research, 2005).

Development organizations have spent considerable time and resources attempting to reduce or eliminate mercury use at ASM sites. The UNEP has a goal of reducing mercury use in ASM by 50% by 2020 (United Nations Environmental Program, 2011), and aid organizations, scholars, and a handful of small companies have endeavored to develop gold recovery technologies that reduce or eliminate the need for mercury. These interventions are commonly aimed at persuading miners to adopt new technologies and are deployed under the assumption that alternative technologies will improve miners' gold recoveries and reduce the negative impacts on the environment and human health of mercury-based technologies (Aubynn, 2009; Hylander et al., 2007a,b; Teschner, 2013).

As early as the late 1990s, development practitioners attempted to introduce new gravity separation techniques including centrifuges, shaking tables, and improved sluices. They believed that these systems would draw miners away from more traditional
systems and increase recovery rates while reducing mercury use (Hentschel et al., 2003). More recently, the “Clean Sluice” technologies developed by Cleangold, LLC have been demonstrated in Peru (Veiga et al., 2006a,b), and programs at larger-scale ASM sites have experimented with centralized milling and leaching plants modeled after conventional large-scale mining technology (Veiga et al., 2009). Isolated projects have been shown to improve gold recoveries and reduce mercury use (Hylander et al., 2007a,b; Veiga and Baker, 2004), but these technologies have had limited success in widespread implementation. It is not always clear why this is the case, but some scholars suggest that these improved concentration methods are often difficult to master and require equipment, parts, and electricity that are sometimes difficult for miners to acquire (Hinton et al., 2003).

Despite the fact that these interventions are billed as boons to miners’ gold recovery, only a limited number of studies on recovery rates of miners’ existing technologies have been documented in the literature. It is worth noting that Hentschel et al. (2003) opine that “Local techniques have frequently undergone evolutionary optimization processes over decades of use. [Therefore], the recovery rates of artisanal miners are often underestimated.” This is somewhat of a contradiction (or perhaps correction) of their groundbreaking report a year earlier (Hentschel et al., 2002) where they defined ASM, in part, by its lack of efficient recovery methods. Unfortunately, current scholars are more likely to reference the older of the two documents.

A study at the Mount Diwata mining area in the Philippines is one of the only reports that extensively compares the use of mercury amalgamation, cyanide leaching, shaking sluices and Clean gold sluices. In the study, the authors tested sluicing and mercury amalgamation processes on the ore from the area and noted that they were relatively ineffective, recovering only 25–35% of the gold. Therefore, it is not surprising that most of the miners in the area had moved away from mercury amalgamation to a milling and cyanidation process even before the researchers conducted their tests. The study showed that the cyanidation process that the miners were actually using had the potential to recover 90–95% of the gold (Hylander et al., 2007a,b).

Studies like this one show that mercury-based processing can be an inefficient process if used on some ore types. However, the geologic and metallurgical conditions at every site are unique. In the case of the Mount Diwata study for example, the miners were working on in situ hard rock deposits (Hylander et al., 2007a,b). The authors note that the deposit had metallurgical complexities, especially multiminerical grains containing gold in chemical and physical bonds, including gold contained within pyrite. Although the Mount Diwata study uncovers important findings for the miners there, it would be entirely inappropriate to apply the results of that study to many other locations, especially the alluvial deposits like the one examined here.

What the Mount Diwata study illustrates is that artisanal miners are entrepreneurial when it comes to new technologies. Miners there were quick to adapt their processing methods to the characteristics of the ore they are mining. This type of technology adoption at ASM sites has been widely documented throughout the world, including in Ghana (Hilson, 2002; Hilson and McQuilken, 2014; Teschner, 2012), Mali (Hilson, 2013; Teschner, 2014), Suriname (Heemskerk, 2011), and elsewhere in the Philippines (Verbrugge, 2014). Although scholars have not followed up these observations with formal recovery studies like the one conducted at Mount Diwata or the one discussed here, it is evident that miners will quickly adopt new technologies when these technologies are able to improve their yields and profitability.

Despite these realities, scholars and development practitioners continue to claim that ASM is inefficient by definition (Peru Support Group, 2012; Hentschel et al., 2002; United Nations Economic Commission for Africa, 2011, pp. 70–71; Veiga et al., 2006a,b), even though there is overwhelming evidence that some ASM activity is quite efficient and that relatively inefficient operators are constantly improving. The unverified assumption that a specific ASM process, group, or site is inefficient can lead to the false conclusion that new technology represents a silver bullet for solving ASM’s litany of problems: If only well-educated development practitioners and western scholars could develop a more efficient method of mining and processing gold ores that is environmentally friendly and safe, then they will be able to address challenges such as mercury pollution, and occupational health and safety problems; and formalize ASM by attracting miners to the low grade, government-established, formalized mining zones (Aubynn, 2009; Hilson, 2006, 2009; Teschner, 2013; Veiga et al., 2009).

4. Study area

Artisanal and small-scale mining is the primary economic activity for rural populations in the gold-rich interior regions of the Guianas (Cuedron et al., 2006; Heemskerk, 2011; Vieira, 2006). Approximately 80,000 people work in the three counties as miners or in occupations that directly support mining activities and mining camps such as equipment and fuel suppliers, sellers of dry goods, commercial sex workers, restaurant workers, and fuel suppliers (Heemskerk et al., 2015; Legg et al., 2015; McRae, 2014). This economic activity primarily operates informally, but it is nevertheless a critical piece of each country’s economy; the unregulated ASM sector in Suriname alone is valued at an estimated $1 billion annually (Gurmendi, 2012).

Foreign migrants play an important role in the ASM sector in the Guianas. Perhaps the most visible are migrants from Brazil. Some scholars estimate that 75% of the ASM workers in the Guianas are Brazilian (de Theije and Heemskerk, 2009; Heemskerk, 2011), and anecdotal evidence from this study suggests that Brazilians have a substantial, if not majority, presence in the ASM properties in the greater study area. Brazilian mining groups commonly “lease” mining land from local land bosses according to informal land tenure systems. Local community residents interviewed for this study characterized Brazilian miners as highly skilled in alluvial gold prospecting and recovery and credited the Brazilians for technological advances in the ASM sector, such as the introduction of hydraulic mining (see Fig. 1).

The miners in the study area mine alluvial deposits that are almost certainly the eroded reflection of a large epithermal gold system located in the immediate proximity. The primary deposit has been subjected to extensive lateritic weathering, as is typical in tropical regions throughout the world. The result is that the entire surface of the landscape is covered with an iron-oxide-stained clay that is often tens of meters thick. Lateritic weathering of gold bearing zones causes an important transformation of the character of gold grains relative to the unaltered rock in which they were originally deposited. Colin and Vieillard (1991) observed that lateritic weathering liberated gold from multiminerical grains resulting in rounded “free gold” grains that could be easily eroded and redeposited in alluvial systems, thus setting the geologic stage for ASM in the study area.

Hydraulic mining, a mechanically assisted form of gravity separation, is the dominant mining method reported across the Guianas (Heemskerk, 2011) and is the method the miners use in the study area. Fig. 1 shows the major components of this mining system. Mining groups use excavators to remove overburden and pile ore

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1. At the time of this study, a large-scale multinational mining company had started construction on a mine to exploit the primary, epithermal deposit.
material at the end of a trench. Miners then wash the ore material with high-pressure hoses powered by a diesel water pump creating an ore-water slurry, which washes down the trench and into a sump. A second diesel pump, called a hydraulic elevator, sucks the water-ore mixture out of the sump and into a sluice. Gold particles and other heavy minerals are captured on the carpets of the sluice. When a mining group is ready to recover the gold, they remove the carpets from the sluice and wash them into a large bucket. The material is then panned by hand to separate the gold from the remaining heavy minerals. This final recovery process can happen as often as three times per week if the group has found a high-grade zone. However, mining groups working lower grade deposits may wait two weeks or more to clean the sluice.

5. Experimental method

The research team collected the data for this study on May 23 and May 27, 2015 from a single mining group operated by Brazilian workers. Geologic samples were collected while the mining team was actively operating. The researchers interviewed the miners (in Portuguese with the aid of a translator) about their mining process, mercury use, and gold marketing activities throughout the two-day sampling process.

This study recognizes the challenges associated with sampling alluvial gold deposits and the need to collect large-volume samples in order to represent the heterogeneity of the orebody and minimize the nugget effect (MacDonald, 1983, pp. 227–230). Importantly, this study does not attempt to value the orebody, but instead the efficiency of the gold recovery method used on the orebody. Nevertheless, the likely heterogeneity of the site must be respected and an analysis of the largest volume samples possible undoubtedly improves the method’s accuracy. Unfortunately, collecting, shipping, and analyzing large-volume samples is impractical, a problem noted by other scholars who have attempted to test alluvial processing systems (Phoon and Williams, 1991). This study manages this challenge by collecting approximately eight kilograms of material for each sample and splitting each into an approximately one-kilogram sub-sample at the field site to send to the lab.

Well-designed gravity separation methods are able to recover gold particles relatively efficiently down to approximately 30 μm. However mercury amalgamation, the process that miners employ when cleaning the sluice, works best on gold grains larger than 75 μm (MacDonald, 1983, p. 389; Mitchell et al., 1997). For this reason, MacDonald (1983) notes that many alluvial processing systems immediately separate and discard all sub-75 μm sized material from the ore in a process known as desliming. Miners deslime their ores for two reasons: First, efficient recovery of gold grains smaller than 75 μm often requires specialized processing methods (like cyanidation) that are prohibitively expensive to implement. Second, ores with greater than 5–6% “slime” can decrease the efficiency of gravity separation methods (MacDonald, 1983, p. 387).

Therefore, the sub-75 μm portion represents an important fraction of the ore material to understand when considering the recovery of any gravity separation system.

In addition to very small particles, alluvial gold processing efficiency can also be limited by large size material. The most obvious challenge with large particles is that they are more likely to be multimineralic. A multimineralic grain may contain gold, but also other gangue minerals (in the case of this study area, most commonly quartz). For example, gold has a density of 19.3 g per cubic centimeter (g/cm³), while quartz has a density of 2.65 g/cm³. A multimineralic grain of 5% gold and 95% quartz would therefore have a density of only 3.5 g/cm³. Despite the fact that this grain contains a large amount of gold, it would likely be washed out the bottom of the sluice. This study uses 500 μm as the lower bound of this large sized material modeled after findings in Mitchell et al. (1997).

Sixteen samples were collected from the site over a period of two days. Eight samples were taken from material that was about to enter the hydraulic elevator (referred to as “ore samples”) using a post-hole digger, and eight samples were taken from the sluice discharge (referred to as “tailings samples”) by placing a sample bag directly under the flow of material exiting the sluice (see Fig. 2). In both cases, the sampler collected approximately eight kilograms of material in large reverse-circulation sample bags designed for retaining fine material.

Immediately after collection, each sample was run through a riffle splitter to reduce the sample to approximately three kilograms. During the riffle-splitting process, the sampler split out four duplicate samples: two ore samples and two tailings samples. Three of the duplicate samples (Ore-8, Tails-7, and Tails-8) returned gold assay results within 5% of their pair. The laboratory was only able to return partial results from one of the Ore-7 samples due to mishandling of the sample.
The twenty samples (sixteen primary plus four duplicates) were dried in a sample oven, and then split them using a rotary splitter to reduce each sample to approximately one kilogram. The one kilogram samples were sent to a professional laboratory in the United States where they were each sieved into the three size distributions: <75 µm, 75–500 µm, and >500 µm. These three sub-samples were weighed and separately assayed for gold. The <75 µm portions were tested using a standard fire assay while the 75–500 µm, and the >500 µm portions were pulverized, homogenized, and screen fire assayed. The two largest grain-size portions were also subjected to a gravimetric finish in order to capture any coarse gold nuggets that may have been present in the sample.

Understanding and verifying miner’s ore-processing activities is key to appropriate interpretation of this study’s results. For example, the miners at the site in this study reported that they used mercury, but that they only used it when they “cleaned” the sluice after a few days or weeks of mining, and there was no mercury introduced within the bounds of the sluicing system being tested. However, other miners interviewed in the surrounding area reported a wide variety of mercury use both in quantity and technique. Some groups reported adding large amounts of mercury directly to their sluices throughout the sluicing process or to the ore sump immediately before the ore material enters the hydraulic elevator, or even to the original ore pile in a process called whole-ore amalgamation.

How mercury is being used changes the interpretation of this study’s results and may change a practitioner’s recommendations for possible mercury-reduction technologies. Therefore, the research team attempted to verify the claim that the miners did not add mercury before the sluicing system. The team collected water and rock samples of material exiting the sluice and tested them both for mercury. Both samples returned no detectable mercury, seemingly corroborating the miners’ claim (Borrillo-Hutter, 2016). Nevertheless, the authors recognize that one-off sampling could easily lead to false negatives, and other miners in the area expressed skepticism that the group was not adding at least small amounts of mercury to their ore piles before sluicing. It is also important to note that the area where the miners were working had been repeatedly mined and re-mined in the years prior to the study. Therefore, even if the group is not adding mercury early in their current processes, it is possible that the orebody contains residual mercury from previous mining activities that is assisting in the current miners’ gold recovery processes.

In addition to the geologic samples, the research team collected environmental samples in the immediate and broader study area (Borrillo-Hutter, 2016), and anthropological data on ASM in the local area (Smith et al., 2017) which added a larger context to this study. Over twelve days surrounding and concurrent with the geologic sampling in this paper, the team conducted interviews in local villages, the town center that services the local mining activities, other active ASM mines, and a nearby large-scale mining company’s camp. These interviews included discussions with land bosses, equipment owners, other artisanal and small-scale miners, community leaders, other community members, shop owners, commercial sex workers, and the large-scale mining company’s employees.

6. Results and discussion

On average, the ore samples entering the sluice contained 0.852 (ppm) gold, and the tailings material exiting the sluice contained 0.077 ppm gold, resulting in an average measured recovery of 91.0% (see Table 1). This recovery rate should be considered strong and suggests any attempt to improve the gravity separation methods employed by this mining group would have only a limited opportunity to improve gold capture. Nevertheless, the results of this study do point to other areas where development practitioners may have opportunities for beneficial technological interventions.

First, the two sub-500 µm fractions represented approximately 25% of the total mass of the sample, yet they contained nearly 100% of the gold. This is not surprising because the deposit had been mined repeatedly for many years, and the miners reported that they very rarely recovered any nuggets, only “flour gold.” The lab results confirm these reports, most likely because miners had already recovered any coarser grained gold years ago. These miners were probably using inferior technologies to those employed by the current miners, and as a result, left behind the finer grained gold that miners are currently finding. These results also indicate that miners are not losing gold by failing to crush the larger material, since it does not contain any gold in the first place.

Second, the sluice is effective at recovering both 75–500 µm sized gold grains and also <75 µm sized gold grains at a greater than 90% rate. An important caveat to this finding is that the hydraulic mining process begins by mobilizing ore with high-volumes of turbulent water. This means that very fine-grained material is put into suspension even before it enters the sump and is not settling out of the slurry until it exits the sluice and has had significant residence time in the tailings pile. Since this study chose to isolate the sluice by sampling ore material from the sump and the sluice discharge, rather than the ore stockpile
and the tailings pile, any very fine grained material contained with the ore stockpile or the tailings piles was probably lost to the sampling process.

Because very fine material takes time to settle out of suspension, the authors speculate that the <75 μm fractions of both ore and tailings samples shown here actually represent material that is on the larger size of the range. Although it is reasonable to conclude that the sluice measured here is well designed for recovering fine-grained gold, we should expect that it suffers from the same grain-size limitations as other well-designed sluices, which are ineffective with material smaller than 30 μm. This finding indicates that up to 98% of gold between 75 μm and 500 μm, and up to 65% of gold <75 μm can be recovered.

Although this study relies on a fairly small sample size, basic statistical analyses show that the sample size is sufficient to warrant the study’s conclusions [Table 2]. First, the mean, maximum, and minimum values of the ore samples show that the ore entering the sluice varies considerably in gold grade throughout the sampling process. Samples Ore-5 and Ore-6 have gold grades of 2.780 and 3.111 ppm respectively, while the remaining samples average only 0.150 ppm. This condition is consistent with the expectation of a heterogeneous ore body and indicates that the sampling method captured some of the variability associated with the “nugget effect.” In practical terms, it shows that the vast majority of the material the miners are processing has very little value and that the group recovers most of their gold when they mine though small, high-grade pockets.

A series of T-tests on the two sample sets show that the sluicing process is almost certainly responsible for the gold grade reduction between the ore and tailings sample sets with greater than 98 percent confidence in both the <75 μm and the 75–500 μm grain sizes. However, T-tests also indicate that it is likely that the sluice or sampling process is altering the 75–500 μm grain size portion (p < 0.05), thus changing the grain size distribution of the samples. The authors hypothesize that the sampling method introduced this change, as ore samples taken before the material entered the hydraulic elevator were collected under less turbulent conditions than tailings samples collected immediately from the bottom of the sluice. Therefore, 75–500 μm size material was more likely to have been in suspension in the tailings samples (and therefore not captured in the tailings samples) compared to the ore samples. The tailings samples contained very little gold, with many values close to or below the detection limit of the analysis. Therefore, the effects of the disparity in grain size distribution between the ore and tailings samples is probably immaterial.

Table 1
Gold recovery analysis results.

<table>
<thead>
<tr>
<th>Ore samples</th>
<th>Total sample</th>
<th>&lt;75 μm</th>
<th>75–500 μm</th>
<th>&gt;500 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Au (ppm)b</td>
<td>% of Total weight</td>
<td>Au (ppm)</td>
<td>% of Total weight</td>
</tr>
<tr>
<td>Ore-2</td>
<td>0.099</td>
<td>0.6%</td>
<td>0.980</td>
<td>18.4%</td>
</tr>
<tr>
<td>Ore-3</td>
<td>0.214</td>
<td>1.2%</td>
<td>2.450</td>
<td>28.9%</td>
</tr>
<tr>
<td>Ore-4</td>
<td>0.081</td>
<td>2.5%</td>
<td>1.280</td>
<td>36.5%</td>
</tr>
<tr>
<td>Ore-5</td>
<td>2.780</td>
<td>0.5%</td>
<td>21.200</td>
<td>25.2%</td>
</tr>
<tr>
<td>Ore-6</td>
<td>3.111</td>
<td>0.3%</td>
<td>17.600</td>
<td>17.8%</td>
</tr>
<tr>
<td>Ore-7</td>
<td>0.126</td>
<td>1.0%</td>
<td>1.260</td>
<td>23.6%</td>
</tr>
<tr>
<td>Ore-8</td>
<td>0.298</td>
<td>0.5%</td>
<td>4.160</td>
<td>23.3%</td>
</tr>
<tr>
<td>Ore-9</td>
<td>0.103</td>
<td>0.6%</td>
<td>5.960</td>
<td>24.5%</td>
</tr>
<tr>
<td>Average</td>
<td>0.852</td>
<td>0.3%</td>
<td>6.861</td>
<td>24.8%</td>
</tr>
<tr>
<td>Tailings samples</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tails-1</td>
<td>0.030</td>
<td>0.8%</td>
<td>0.590</td>
<td>0.179</td>
</tr>
<tr>
<td>Tails-2</td>
<td>0.034</td>
<td>0.5%</td>
<td>&lt;0.05</td>
<td>20.2%</td>
</tr>
<tr>
<td>Tails-3</td>
<td>0.025</td>
<td>0.7%</td>
<td>&lt;0.05</td>
<td>16.2%</td>
</tr>
<tr>
<td>Tails-5</td>
<td>0.179</td>
<td>0.9%</td>
<td>0.880</td>
<td>25.8%</td>
</tr>
<tr>
<td>Tails-6</td>
<td>0.271</td>
<td>0.6%</td>
<td>1.390</td>
<td>13.3%</td>
</tr>
<tr>
<td>Tails-7</td>
<td>0.025</td>
<td>0.5%</td>
<td>&lt;0.05</td>
<td>15.2%</td>
</tr>
<tr>
<td>Tails-8</td>
<td>0.025</td>
<td>0.4%</td>
<td>&lt;0.05</td>
<td>13.5%</td>
</tr>
<tr>
<td>Tails-9</td>
<td>0.025c</td>
<td>0.8%</td>
<td>NSSd</td>
<td>28.8%</td>
</tr>
<tr>
<td>Average</td>
<td>0.077</td>
<td>0.7%</td>
<td>0.432</td>
<td>18.9%</td>
</tr>
<tr>
<td>Average recovery</td>
<td></td>
<td>91.0%</td>
<td>93.8%</td>
<td>91.4%</td>
</tr>
</tbody>
</table>

All instances of <0.05 ppm (the detection limit of the analysis) were replaced with 0.025 (half of the detection limit) for the purposes of calculating dependent values.

b NSS = Insufficient sample to run the analysis.

c Weighted average of the three component fractions.

d Weighted average excluding NSS sample fraction.

e This value should not be interpreted to mean that recovery of gold in the >500 μm grain sizes is poor. A better interpretation is that there is hardly any gold in material in the >500 μm grain size as only a single sample in either the Ore set returned a gold value higher than the detection limit of 0.05 ppm (Ore-6, at only 0.06 ppm).

f Based on the average of two duplicate samples.

The tailings samples contained very little gold, with many values close to or below the detection limit of the analysis. Therefore, the effects of the disparity in grain size distribution between the ore and tailings samples is probably immaterial. If one assumes the population of tailings’ grades to be normally distributed, with mean and standard deviation equal to the sample mean and
sample standard deviation, then these data suggest that with greater than 95% confidence, any material leaving the sluice will have a grade <0.262 ppm. These assumptions are difficult to verify with the small sample size in the present study, but the 0.271 ppm tailings sample maximum observed here suggests that this conclusion is reasonable.

7. Implications of this work

The results of this study supply the development practitioner with a palate of useful information with respect to the likely efficiency of technological interventions at an alluvial gold mining site. The sieving and assaying of ore and tailings from ASM sites is relatively simple, and at the time of this study cost approximately $160 per 1-kilogram sample for analysis at a professional laboratory. This method provides a reliable value for the recovery rate of the gravity separation system employed by the miners, a critical piece of gold recovery systems at most ASM sites. In this case, the 91% recovery rate of the miners’ sluice directs a concerned development practitioner away from attempting to improve this portion of the process, since the opportunity to capture more gold is quite low.

An analysis of the gold contained within each grain-size distribution provides a practitioner with some indication of the likely efficiency of mercury amalgamation or other follow-up recovery processes that the miners employ on the sluice’s captured gold and heavies. In this case, more than 90% of the gold being captured by the sluice is sized between 75 and 500 μm, and microscope work confirmed that there was no oxide coatings on the gold grains, the ideal conditions for mercury amalgamation.

Other grain-size distribution and gold content results might direct a practitioner toward different follow-up work. For example, significant gold contained within the >500 μm fraction of ore samples and poor recovery of that gold, as indicated by significant gold remaining in the >500 μm of tailings samples, would suggest that recoveries could be improved by crushing the ore before sluicing. Alternatively, significant gold contained in the <75 μm portion may signal an opportunity for improvement by introducing cyanidation methods, which have been shown to be substantially better than mercury at recovering very small-sized gold grains (although the limitations of the sampling technique at capturing material on the smallest end of the <75 μm size distribution must be respected).

Fig. 3. Gold grains from sample Ore-6 showing free gold grains with no sign of an oxide coating that would inhibit efficient mercury amalgamation.

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Total Sample</th>
<th>&lt;75 μm</th>
<th>75–500 μm</th>
<th>&gt;500 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Au (ppm)</td>
<td>% of Tot weight</td>
<td>Au (ppm)</td>
<td>% of Tot weight</td>
</tr>
<tr>
<td>Ore samples</td>
<td>Mean</td>
<td>0.852</td>
<td>0.9%</td>
<td>6.861</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>3.111</td>
<td>2.5%</td>
<td>21.200</td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>0.081</td>
<td>0.3%</td>
<td>0.980</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>1.214</td>
<td>0.7%</td>
<td>7.463</td>
</tr>
<tr>
<td>Tailings samples</td>
<td>Mean</td>
<td>0.077</td>
<td>0.7%</td>
<td>0.432</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>0.271</td>
<td>0.9%</td>
<td>1.390</td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>0.021</td>
<td>0.4%</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>0.093</td>
<td>0.2%</td>
<td>0.508</td>
</tr>
</tbody>
</table>

Practitioners and scholars who choose to conduct a study like this one on an ASM site of interest are taking a simple, relatively inexpensive step toward understanding the effectiveness of ASM processing methods. By collecting and analyzing samples taken immediately before and after material enters a gravity separation system such as a sluice, separating them by grain size, and testing them for gold, it is possible to measure the efficiency of a gravity separation unit and understand the potential efficiency of miners’ follow-up chemical recovery methods, especially mercury amalgamation.

By understanding where gold is being captured and lost within existing ASM processes, development practitioners can isolate true opportunities for working with miners to improve their mining and processing systems and avoid introducing new technologies that reduce gold recoveries compared to the status quo. By using this tool, practitioners are more likely to achieve effective, sustainable technologies for miners, the environment, and community stakeholders.


United Nations Environmental Program, 2011. Developing a National Strategic Plan to Reduce Mercury in Artisanal and Small-Scale Gold Mining. UNEP, s.l.


United Nations Environmental Program, 2011. Developing a National Strategic Plan to Reduce Mercury in Artisanal and Small-Scale Gold Mining. UNEP, s.l.


