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# The cyanide revolution: Efficiency gains and exclusion in artisanal- and small-scale gold mining

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ABSTRACT

Since its advent at the end of the nineteenth century, cyanide processing facilitated the intensification and global expansion of industrial gold mining. Today, there are important indications that artisanal and small-scale gold mining (ASGM) is on the verge of a similar cyanide revolution: while ASGM is typically associated with mercury-based processing, mercury amalgamation is increasingly replaced with, or complemented by, cyanidation. Relying on evidence from the Philippines, Indonesia, and Burkina Faso, we demonstrate how this transition is having a deeply transformative impact on ASGM communities. On the one hand, cyanidation produces clear efficiency gains. Together with rising gold prices, it is fueling a dramatic expansion of ASGM by enabling the profitable extraction of lower-grade gold deposits. On the other hand, it contributes to the emergence of new and often highly unequal labor and revenue-sharing arrangements. More broadly, these findings demonstrate the highly uneven impact of socio-technical transformations. Consequently, the growing number of efforts to intervene in the technological make-up of ASGM, usually in the name of efficiency and sustainability, should be wary of having unintended consequences.

## 1. Introduction

In recent decades, gold mining expanded from its historical core (South Africa, the United States, Canada, Australia, and Russia) into a wide range of new gold mining regions, many of them located in the global South (Verbrugge and Geenen, 2020). In addition to the expansion of large-scale industrial mining, many of these regions have witnessed a notable increase in artisanal and small-scale gold mining (ASGM). Commonly described as low-tech, labor-intensive gold extraction, ASGM has become a catch-all term for an exceedingly wide range of activities that operate with varying degrees of capital and labor intensity (e.g., Ferring et al., 2016; Verbrugge and Geenen, 2020; Libassi, 2020a). While considerable attention has been devoted to technological innovations in artisanal and small-scale gold *mining* (e.g., Mabhena, 2012), technological innovations in gold *processing* have hitherto received less attention. Instead, the predominant focus of academics and policy-makers continues to be 'the mercury problem' (Esdaile and Chalker, 2018). Mercury, which is used to extract gold from ores, is often released during processing activities, with potentially dire consequences for human health and for the environment. While mercury amalgamation remains the processing method of choice in many ASGM-regions, evidence is emerging that it is increasingly complemented or even replaced with cyanide processing methods (Gonçalves et al., 2017; Massaro and De Theije, 2018). In line with research on mercury use in ASGM, existing studies have focused mostly on how cyanidation impacts human health and/or the environment, while paying only scant attention to the social impacts of cyanidation (Guimaraes et al., 2011; Leung and Lu, 2016; Nyanza et al., 2017; Knoblauch et al., 2020). Where this impact has been considered, the focus lies on emerging inequalities *between* ASGM producers, on the one hand, and the owners of processing facilities on the other (Veiga et al., 2014; Bansah et al., 2018).

This article sets out to explore how the diffusion of cyanide processing affects dynamics of inclusion and exclusion in gold mining areas. In doing so, it extends previous scholarly critiques that argue dominant modes of ASGM governance are often overly technical, and thus gloss over social unevenness and power dynamics within the sector (e.g., Fisher, 2007; Hilson, 2008; Spiegel, 2017; Buss et al., 2021). We start with a short historical overview of cyanide processing in industrial gold mining, where it facilitated trends towards consolidation and expansion. In the third section, we present three case studies of how cyanidation is changing the face of ASGM the Southern Philippines, West Java (Indonesia), and Burkina Faso. The cases highlight that, although

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cyanidation has typically led to an intensification of gold production, the distribution of benefits from this innovation is often highly skewed. In the final section, we consider the policy implications of our findings.

## 2. Cyanide in industrial gold mining

### 2.1. History

Until the end of the nineteenth century, mercury amalgamation was the most widely used processing method in industrial gold mining. In 1887, a team of chemists and physicians from Glasgow developed what became known as the Macarthur-Forrest cyanidation process. In essence, it involves the dissolution of gold in a dilute cyanide solution, which is then brought into contact with zinc, so that the gold will precipitate (Habashi, 2016). The introduction of cyanide processing revitalized the South African mining industry. By the 1880s, higher-grade near surface deposits in the country had nearly been exhausted, and the deeper and more fine-grained gold could not be extracted using traditional (surface) mining methods and mercury amalgamation. The introduction of the Macarthur-Forrest process in 1890 enabled the profitable extraction of lower-grade ores, which in turn led to the emergence of deep-shaft mines that were controlled by a small number of large, vertically organized finance houses (Richardson and van Helten, 1984). In other words, the advent of cyanide processing contributed to a process of expansion and consolidation in the South African gold mining industry (Fivaz, 1988).

Throughout the twentieth century, the cyanidation process underwent further improvements. In the 1950s, the US Bureau of Mines developed new methods that involved applying activated carbon to a cyanide solution in order to capture gold particles (Habashi, 2016). In the 1980s, heap leaching (which involves a large pile or 'heap' of ores being sprayed with a cyanide solution) and activated carbon-based technologies (prime amongst which is carbon-in-pulp processing, which takes place inside large tanks) became increasingly widespread (Mooiman et al., 2016). Combined with increased demand and rising prices, these innovations in cyanide processing led to dramatically improved value-to-volume ratios in gold mining. This, in turn, facilitated the revival of older gold mining destinations like the US and Australia, as well as the expansion of gold mining into new gold mining destinations (Mudd, 2007; Verbrugge and Geenen, 2020).

### 2.2. Social and environmental impacts

Despite this improved efficiency, accidents at mines around the globe raised alarm over cyanide processing. In most cases, cyanide was released into the environment due to damages in heap leach liners or spillages from overflowing solution ponds or tailings storage areas (Hilson and Monhemius, 2006). The most infamous example is the Baia Mare cyanide spill in Romania in 2000, where 50–100 tons of cyanide were released. While cyanide occurs and degrades naturally in the environment, high concentrations of cyanide pose significant (and possibly lethal) threats to the human and non-human environment. The chemical properties and toxicity of cyanide depend on various factors, including its exposure to light and air, and the presence of other metals. One combination that is particularly relevant to ASGM are mercury-cyanide complexes, which form and persist when mercury-contaminated tailings are reprocessed with cyanide (Veiga et al., 2014). The addition of cyanide makes mercury more easily methylated and more bioavailable (i.e., it can be more easily absorbed by living organisms), and therefore poses exponentially greater health risks. In short, reprocessing mercury-contaminated tailings with cyanide, in an environment where health and safety regulations are limited to non-existent, is a dangerous practice (Veiga et al., 2014).

While some of these processes (including the mechanisms through which mercury-cyanide complexes become methylated) are still not entirely understood, there exists broad consensus about the potential human and environmental toll of inappropriate mercury- and cyanide use. What is lacking, however, is a critical analysis of how the diffusion of cyanide processing intersects with local, context-specific social dynamics in gold mining. In industrial gold mining, the introduction of more efficient cyanidation methods in the second half of the twentieth century dramatically improved value-to-volume ratios, which in turn cleared the way for a broader shift from labor-intensive underground mining to 'low-grade, super-large, high-tonnage, and ultra-mechanized' open-pit mining (Darling, 2011p. 4). In the gold mining industry, open-pit mining now accounts for approximately three quarters of global mine production (World Gold Council, 2018). While working conditions in open-pit mines are generally safer than in underground mines, their labor intensity is lower, as open-pit mines require fewer workers to mine the same amount of ore (Nelson, 2011). Moreover, due to its sheer scale, open-pit mining tends to be more environmentally destructive and can have a profound (and lasting) impact on local livelihoods systems (Bury, 2004). Such operations require considerable investments, which plays into the hands of large 'diversified' mining giants like Glencore and Rio Tinto that have gradually expanded their control over the global mining industry (Humphreys, 2015). Still, compared to other mining sectors, the gold mining industry has a relatively large number of small- to mid-tier producers.

### 2.3. Cyanide in ASGM: An exploration

In recent years, a growing body of evidence suggests that cyanidation is spreading from industrial gold mining to smaller mining operations, including those that are conventionally understood as ASGM. In some cases, cyanide is used directly by miners (Langston et al., 2015), in others it is deployed only at centralized processing centers (Veiga et al., 2014), and in still other cases it remains the exclusive purview of industrial mining companies who purchase and reprocess ASGM tailings (Bansah et al., 2018). The technologies used by ASGM participants mimic those used by industrial operations, if often in smaller and slightly less intricate forms. Carbon-in-leach techniques, whether in tanks with agitating mechanisms or simply in soaking ponds, predominate. Gold ores or tailings are mixed with water, cyanide salts, caustic agents, and activated carbon (also called activated charcoal). After being 'cooked' for several days, the gold-laden carbon will be removed and heated to release the precious metal. As illustrated by the case of Burkina Faso shared below, zinc precipitation methods are also used in some cases. Research on the use of these processes in ASGM has thus far been overwhelmingly technical in focus. Analyses have detailed the increased efficiencies associated with cyanide, thereby suggesting a promising opportunity for reducing mercury use; or have catalogued the toxicological dangers of using cyanide in conjunction with mercury (e.g., Veiga et al., 2009; Velásquez-López et al., 2011; Guimaraes et al., 2011).

We address a rather different, but equally important set of social and political-economic questions. Building on the above observations about cyanidation and the intensification of industrial gold mining, the following sections will explore how the diffusion of cyanide processing in the Philippines, Indonesia, and Burkina Faso[1] intersects with structural dynamics in ASGM, and how these structural dynamics in turn affect dynamics of inclusion and exclusion. Methodologically, we ground our analysis in extended periods of fieldwork in mining regions in each of the countries discussed. We use data collected through semi-structured interviews and oral histories with ASGM participants throughout the gold production process, cyanidation plant owners and operators, gold buyers, and local community leaders, as well as through observation of work and everyday life in active mining sites. For each of the countries, we start with a short historical overview of ASGM-expansion, before zooming in on how the advent of cyanidation has differentially affected the fate of those involved.

## 3. The Philippines: The cradle of cyanidation in ASGM?

### 3.1. The informalization of mining

The history of gold mining in the Philippines dates back to pre-colonial times (Caballero, 1996). With the advent of US colonialism at the turn of the twentieth century, the country saw the emergence of a modern mining industry that gradually expanded across the peninsula (Lopez, 1992). While ASGM persisted in different shapes and forms, it started to expand dramatically in the 1980s, notably in Benguet Province on the northern island of Luzon, and in the Davao region on the southern island of Mindanao. Several factors contributed to this expansion, including high gold prices and a depressed economic context, in which a growing number of people were on the lookout for attractive livelihood opportunities (Verbrugge, 2014). Yet ASGM also attracted the attention of local elites, and over time also Chinese and Korean investors, for whom ASGM offered exciting investment opportunities.

This boom in ASGM cannot be understood without taking into account the crisis in industrial mining (Verbrugge, 2015a). Like many other sectors, by the 1980s the mining industry had fallen prey to rent-seeking behavior on the part of a small group of 'cronies' connected to dictator Ferdinand Marcos, and was increasingly facing structural debt issues (Clad, 1992). As a growing number of industrial mines across the country shut down, skilled and semi-skilled mine workers would subsequently deploy their skills in ASGM. In several cases, they were joined by chemists and engineers, who brought along valuable mining expertise, and sometimes even mining equipment from the moribund industrial mining operations.

This process was particularly apparent in the Davao region in Mindanao. In the decades following World War II, this region had been home to a number of industrial mining operations. At that time, ASGM mostly took the form of rudimentary operations involving digging and panning for 'free gold'. While the 1970s and early 1980s saw the introduction of ball mills and mercury amalgamation, processing remained relatively basic as well. This started to change in the mid-1980s, when the biggest industrial mine in the region, APEX mining, fell into disarray. As a growing number of workers turned to ASGM, senior company officials initiated what they referred to as 'the outside project': buying ores and ball mill tailings from surrounding ASGM areas and processing them inside the company compound using cyanidation techniques.

### 3.2. Cyanidation and the advent of medium-scale gold mining

Soon, chemists and engineers from APEX mining and from other industrial mining operations decided to set up their own, independent company: Value Minerals. They constructed what was likely to be the first cyanide processing plant in the Philippines that was not directly linked to an industrial mining operation.[2] Shortly thereafter, a growing number of *plantas* (cyanide processing plants) were constructed in other towns and villages. It is interesting to note that in addition to 'ordinary' mining financiers, local politicians also became heavily invested in cyanide processing. At least in part, this may be due to the fact that setting up a cyanidation plant requires the authorization of local authorities, in the form of business permits, land use permits, etc (Verbrugge, 2015b). By the early 2010s, when a second gold rush enveloped Mindanao, *plantas* could be found in almost every mining village. By 2012, the provincial town of Nabunturan (the capital of present-day Davao de Oro province) alone was claimed to be home to 64 *plantas*, each with one or several tanks with a capacity to process 10–20 tons of ores (or tailings) every few days.[3] By that time, several assay laboratories had been established where miners could have their ore samples analyzed by professional chemists.

Cyanide processing typically takes longer than mercury amalgamation, as ore-bearing material has to be 'cooked' for several days with carbon, limestone, and cyanide, before it can be processed further. Yet the average capacity of a tank is also much higher. In addition to having higher recovery rates (most respondents mentioned 90–95%) than mercury amalgamation (30–35%), cyanidation facilitates the extraction of silver, which typically represents around 10–15% of the recovered minerals. The possibility of having ore samples tested in laboratories also meant that miners were no longer limited to looking for gold veins, but could instead extract more diffuse 'fine gold' that is not readily visible to the naked eye. Finally, cyanidation meant that the tailings (waste) of hundreds or even thousands of ball mills across the region could now be re-processed using cyanide to extract remnant gold, suddenly acquired new value.

In short, cyanidation led to dramatically improved value-to-volume ratios in ASGM, while rising gold prices further increased its profitability, and assay analysis reduced uncertainty. Together, these factors increased the appeal of investing in ASGM, which in turn facilitated the expansion of what is locally referred to as medium-scale mining. Contrary to smaller mining activities that are undertaken by groups of friends or family, medium-scale mining involves bigger tunnels that branch out into side-tunnels (*destinos*) and employ dozens or even hundreds of workers. To varying extents, these mining operations make use of modern technologies like automatic drills, dump trucks (*saddams*), mine carts, and explosives.

### 3.3. Exclusion and the persistence of mercury use

While there should be no doubt that cyanidation has increased the profitability of ASGM, it also had profound effects on who stands (not) to benefit from it. To understand this, we need to delve into some of the intricacies of revenue-sharing. In some of the smaller mining operations, the practice of *graba* (ore) sharing is still practiced. In *graba sharing*, ores are divided between the actual mine workers (who together form a mining team or *corpo*) and their financier(s) (who may similarly unite in a legally registered corporation) according to an agreed-upon revenue-

[1] In all three cases considered, use of cyanide in ASGM largely takes place in spite of, and against, local legislation. In Burkina Faso, the latest version of the national mining code (promulgated in 2015) explicitly forbids the use of cyanide for operators who possess an artisanal mining permit. In the Philippines, cyanide is regulated through the Toxic Substances and Hazardous and Nuclear Wastes Control Act of 1990. Similarly, cyanide use is restricted in Indonesia under Government Regulation No. 101 of 2014 on Management of Hazardous and Toxic Waste and Law No. 32 of 2009 on Environmental Protection and Management. While cyanide can legally be used in these countries, including in (but not limited to) the mining industry, its use is subject to strict registration, licensing, and monitoring requirements—typically not the type of requirements that ASGM-operators meet. Moreover, most of the ASGM activities in these contexts operate informally, without permits of any kind, let alone those required for cyanide use.

[2] Interviews held with the staff of VMI mining, Nabunturan,

[3] Interview with owner of processing plant in Nabunturan, 12–2-2012.

sharing scheme. Over time, *cash sharing*, whereby revenues are distributed once the gold has been processed and sold, became more common. In both cases, ores typically undergo a first round of processing near the mine site. After ores are grinded in a ball mill, mercury is applied to capture the gold. In some cases, cash sharing takes place directly after this first round of processing, so that miners themselves do not benefit from cyanidation. Instead, the tailings accrue to the ball mill owner, who brings them to a cyanidation plant once enough tailings have been accumulated. The owner of the plant will charge a 'custom milling fee' that ranges from PHP 30,000–60,000 (USD 600–1200) per tank with a 10-ton capacity. Over time, a growing number of financiers has invested not only in their own ball mill facility, but also in a cyanidation plant. In some cases, this meant that the initial round of mercury amalgamation is skipped and instead ores are taken straight from mine to plant.

In these cases, cash sharing takes place after the second round of processing in the cyanidation plant. Theoretically speaking, this should allow miners to benefit from the higher recovery rates achieved by cyanidation. In practice, this is not necessarily the case. Bigger operations tend to have highly skewed revenue-sharing mechanisms, whereby the financier(s)—different financiers sometimes form a legally recognized corporation—take(s) anywhere from 30 to 70 percent of the revenues. Any expenses incurred by the financier(s), such as food and shelter for workers, materials, gasoline, processing, etc., are usually deducted from the gross revenues, so that revenue-sharing effectively becomes *profit*-sharing, and investment risk is shared with the workers. The fact that some financiers own their own plant enables them to avoid the cost of custom milling, which is instead displaced onto the workers. Moreover, revenues from any silver contained in the ores are not included in the revenue-sharing. More broadly, cash sharing leaves ample scope for cheating on the part of the financiers. At least in part, this is related to the process of cyanidation itself: as ores from different tunnels and operations (but from the same financier) are mixed together in one 'batch', it becomes virtually impossible for workers to determine the revenues their tunnel has generated. As a result, miners have to content themselves with an envelope that contains a seemingly arbitrary sum of money. This situation also explains why many (mostly informal) landowners attempt to negotiate their royalty share in *graba* (rather than cash), which is subsequently processed in their own ball mill.

In addition to financiers and plant owners—who are sometimes one and the same person—there are other rent-seekers that directly or indirectly benefited from the advent of cyanidation. Local politicians can impose taxes and fees on processing plants, or on ore transport from the mines to the processing plant. In other cases, local politicians or communist rebels of the New People's Army send people to processing plants to collect 'campaign contributions' or 'revolutionary taxes'. Most importantly, many politicians are not only heavily invested in gold mining and/or gold buying, but also in gold processing. In these activities, they use their prerogatives as local politicians to maintain and expand their control over the local gold mining economy (Verbrugge, 2015b).

As was already indicated in the description in the preceding section, cyanidation has by no means led to the phasing out of mercury. Why is it that despite the widespread availability of cyanide processing, mercury amalgamation is still so widely used? In some cases, mercury is used as part of the exploration process, to assess the gold content of an ore sample. In other cases, the persistence of mercury amalgamation can be seen as a by-product of the exclusionary nature of cyanidation. For many of the smaller operations, cyanidation is simply inaccessible: they are unable to amass the amounts of ore needed to fill a tank, and even if they could, they would be unable to afford the custom milling fee. More importantly, they need regular cash income to survive and to maintain their mining operations. Mercury amalgamation provides quicker returns than cyanidation, and requires far fewer capital inputs.

In still other cases, like the example of landowners demanding royalty shares in *graba* rather than cash to process ores in their own ball mill, the use of mercury can be seen as a desperate attempt on the part of weaker actors in the value chain to counteract the exclusionary practices of stronger actors (notably big financiers). A telling example comes from the northern Province of Benguet, where Benguet Corporation worked out a highly unequal arrangement with ASGM-contractors. While the latter are responsible for the actual mining, the company is in charge of maintaining the main tunnel portal, and of processing and selling the gold. In exchange, Benguet Corporation retains a disproportionate share of the revenues (for more details on this arrangement see Verbrugge, 2017). Confronted with these exclusionary practices, some of the workers have reverted to a process known as 'highgrading': processing high-grade ores using mercury inside the tunnel. In short, our analysis of cyanidation in the Philippines also sheds light on the social origins of persistent mercury use.

## 4. Indonesia: uneven impacts of cyanide's socio-technical transformation

### 4.1. Gold histories and the spread of cyanide

The Indonesian islands have been famed for gold since antiquity, when Hindu and Arab merchants traded for gold from the Sumatran highlands. This artisanal extraction blossomed into a modern, informal mining boom beginning in the late 1980s as ASGM activities expanded alongside an influx of foreign-financed corporate mining expeditions (see Aspinall, 2001; Williams, 1988). Shortly thereafter, informal gold mining experienced a spike in the wake of the 1997 Asian financial crisis, becoming both a livelihood refuge and an investment opportunity (McMahon et al., 2000). Since then, persistently high gold prices and the introduction of more advanced mining techniques, including gold cyanidation, have further consolidated the strength of the sector. Today, ASGM is a massive and highly mobile sector that spans the Indonesian nation. Approximately one million people depend on the sector for livelihoods across some 900 locations in 27 of Indonesia's 34 provinces (BaliFokus, 2017). Remarkably, Indonesia's most significant recent gold discoveries—those in Bombana, Sulawesi (2008), and Gunung Botak, Maluku (2011)—were made by ASGM participants, and not by industrial mining.

Although mercury amalgamation continues to be the most ubiquitous form of ASGM processing in Indonesia, at least two gold cyanidation techniques are commonly used. *Tong* (or *gentong*, named after the cylindrical vat used) is a method best suited for extracting remnant gold from tailings which have already been treated with mercury. Tailings are mixed with sodium-cyanide pellets, caustic lime, and activated charcoal and agitated in a large tank for approximately two days. Afterwards, the carbon is removed and either superheated or amalgamated with mercury to recover the gold. A second technique, called *rendaman* ('soaker'), involves treating gold ore in a tarp-lined pool dug into the ground. This method requires similar inputs to the *tong* method, but is used for processing large volumes of low-grade ores, generally in looser sediments, that have not yet been treated with mercury.

These cyanidation techniques have become increasingly widespread since the mid-2000s. One theory posits that the technologies were imported from the Philippines, spreading across the Celebes Sea and first becoming established in North Sulawesi around 2001 (see Whitehouse et al., 2006). From there, gold cyanidation has disseminated to most other ASGM regions in Indonesia, including West Java, Banten, Central Kalimantan, South Kalimantan, West Nusa Tenggara, Aceh, and Maluku (Krisnayanti et al., 2012; Spiegel et al., 2018; author's fieldwork). In many of these regions, the socio-technical organization of gold production has historically been oriented around mercury processing. Little is known about how the expansion of cyanide-based processing has affected the social relations and experiences of mining participants. Below, we explore this influence through the case of Pongkor, a region in West Java where ASGM activities have persisted for over twenty-five years.

### *4.2. The emergence of the tailings economy*

Cyanidation technologies first appeared in Pongkor around 2007. By that time, mercury-based ASGM activities had been common in the region for at least a decade and informal gold production had coalesced into a relatively ordered, and socially embedded, part of the local economy (Libassi, 2020b). The introduction of cyanidation techniques had a transformative effect on this sector almost immediately. Local stories indicate a Korean or Chinese man[4] opened the first cyanide processing plant in Pongkor. He moved to a local village and quickly began buying up all the tailings he could find. These tailings, having already been processed with mercury once or twice, were considered worthless. The common name for tailings, *lumpur*, suggests as much—it simply means 'mud'. The man was able to purchase huge quantities of tailings at a low price and, after re-processing them with his more efficient *tong* cyanidation technique, accumulated huge profits from the residual gold extracted. Miners at this time recall the bewilderment, first, at having someone interested in buying their *lumpur*, and, second, at the realization that they had been swindled out of significant quantities of gold.

Soon, the use of cyanidation techniques spread and the price of tailings grew. The advantage of cyanide's early adopters diminished, but the community's relationship to *lumpur* had forever changed. Tailings became a valued resource—even a traded commodity—around which new markets, jobs, and business opportunities arose. Whereas previously tailings were disposed of haphazardly, today it is meticulously collected in basins adjacent to the rotating mills, called *gelundung*,[5] used for mercury processing. In fact, these tailings are now an important source of income for the many families in Pongkor who own *gelundung*. These families invite miners to process ore in their mills at no cost, having previously charged a 'rental' fee, and keep the tailings as compensation for the use of their equipment. Those collecting *lumpur* can sell it for cash or try to re-process it themselves, generally paying a *tong* entrepreneur for cyanidation services. *Lumpur* traders scour the villages in small trucks, brokering with *gelundung* owners for the tailings they have accumulated. Owners who are in immediate need of cash will readily sell. Those who can afford to will wait, knowing better returns can be had by cutting out the middleman. Traders, meanwhile, derive profits by carefully assessing the gold contents of the mud. Some even claim that they can determine where the original ore was extracted by simply smelling the sediments. Other men make their livelihood simply in the transportation of tailings. They can often be seen riding their motorcycles up and down the narrow village paths, covered from head to toe in mud. Finally, some local residents attempt to make a buck by searching for, and digging up, gold-laden tailings disposed of and forgotten in local soils decades prior.

### *4.3. Intensification and differentiation*

In addition to spawning a parallel gold economy oriented around tailings, cyanidation techniques have enabled the intensification and expansion of primary ore extraction in Pongkor. First, greater efficiencies mean more gold is extracted from the same ore. For well-capitalized operations that produce large volumes of ore, this has had a dramatic effect. These intensified operations can bring all processing steps—from crushing, to mercury amalgamation, to cyanidation—'in-house', resulting in significant economies of scale. A second effect of cyanide is the expansion of the sector into lower-grade primary ores. With improved efficiencies, miners can now profitably dig tunnels in areas once considered devoid of meaningful gold content. This spatial expansion has had significant knock-on effects. In the Pongkor region, the highest concentrations of gold are located on a mining concession controlled and policed by an industrial mining company. With cyanide, lower-grade ore operations are now popping up outside the mining concession. These areas have significantly less pressure from police and miners there operate with relative impunity. For example, whereas mining on the concession cannot involve permanent 'camps', operations outside the concession construct lodging for laborers and processing centers directly adjacent to their tunnels. Free of the need for discretion, these operations experience significant cost savings and can work at larger scales.

While cyanidation has improved gold yields, it has simultaneously reproduced and exacerbated some forms of inequality in Pongkor. Cyanide processing requires significant amounts of capital, equipment, and expertise. Its benefits are also correlated with scale: relatively large volumes of tailings or ore are needed for a single batch.[6] These factors mean that only those who are already well-positioned—such as wealthy mining bosses and other local elites—typically own cyanidation facilities. The majority of miners continue to primarily use mercury amalgamation. Thus, relatively few ASGM participants are poised to accrue the full benefits of cyanide. The reprocessing of tailings is illustrative of this unevenness. Miners who operate at modest scales typically wait weeks or months to accumulate enough *lumpur* for one round of cyanidation. After they have, they then sell these tailings to a trader (receiving 30,000–50,000 rupiah per sack) or pay a rental fee for the use of *tong* equipment. Either way, they lose a significant portion of their potential revenues. Highly capitalized operations, on the other hand, utilize their own cyanidation equipment and have sufficient stockpiles of inputs to operate them almost continuously. Additionally, only well-financed operations can take advantage of newly profitable low-grade ores that necessitate the use of cyanidation techniques. More common miners, who must rely on cheaper mercury processing, continue to be limited to higher grade ores, which are both more difficult to find and are more heavily policed.

Cyanidation has also sparked new inequalities inside mining operations. This is most evident in the altered labor relations found in the most intensified, cyanide-deploying mining operations. Historically, most tunnel workers in Pongkor have been compensated via ore sharing arrangements: laborers receive a portion of the rock collected each day and, after returning to the village, process it using their own mercury amalgamation equipment (see also Libassi, 2020b). With the introduction of cyanidation techniques, more operations are now processing their ore in a collective batch. This is particularly true for operations that process large volumes of sediments with relatively low concentrations of gold, as these ores can only be processed using the *rendaman* technique. All such operations now pay their workers in cash, rather than the customary ore. In theory, these cash payments represent shares, but, in practice, they appear increasingly wage-like. Laborers are often paid a relatively stable amount in cash every two weeks. Calculations are opaque, and this has raised suspicions about how compensation is determined and how much revenue is being diverted to financiers. Laborers in these types of mining operations also tend to have less autonomy than others in Pongkor and are easily replaced. In general, they are more dependent on the mining elites that employ them, often including living and purchasing rations at barracks constructed by their bosses. Cyanidation has thus led to less preferable terms of employment for some poorer mining participants, further exemplifying how the distribution of benefits from cyanide processing has been highly uneven.

[4] Because of the way race and ethnicity are commonly spoken about in Indonesia, it is difficult to determine if this man was indeed a foreign national, or rather an Indonesian citizen of East Asian descent.

[5] In other parts of Indonesia this equipment may be referred to as a *tromol*.

[6] *Tong* and *rendaman* equipment vary dramatically in size, with capacities ranging from 25 to 300 sacks of ore or tailings. The smaller sizes are more accessible to less-wealthy miners, but even they require a much greater volume of inputs than mercury processing.

## 5. Burkina Faso: cyanide and reconfigurations of power in ASGM

### 5.1. The rise of 'orpaillage' since the 1980s

Despite debates on the exact locations and impacts of early historical extractive activities, scholars agree that alluvial gold mining has a long history in certain regions of present-day Burkina Faso (cf. Werthmann, 2007). Attempts by the French colonial government to promote and industrialize gold mining were limited: a mine was opened in Poura in 1938 but remained unproductive and was closed shortly after the country's independence (cf. Bantenga, 1995; Kevane, 2015). In the early 1980s, while industrial activities in Poura were briefly—though unsuccessfully—revived by the government, more intensive forms of ASGM appeared in northern Burkina Faso, with the digging of shafts and underground tunnels to target hard-rock deposits. The French word *orpaillage*, originally referring to manual panning near rivers, started to indicate any non-industrial form of gold mining, including the increasingly sophisticated techniques used by these diggers. The peak in gold prices offered an important incentive to this development, but so did a series of drought years in the Sahelian regions that pushed many people out of subsistence farming in search of alternative livelihoods. Artisanal mining gradually expanded to other regions of the country, and by the early 2000s ASGM was a consolidated sector with hundreds of active mining sites and thousands of workers across the country.

In the meantime, with the mining acts (*codes miniers*) of 1997 and 2003, the government revised legislation to encourage the growth of a competitive mining industry (Luning, 2008). These reforms also affected ASGM, as the gradual demise and the final abolition (in 2006) of the Comptoir Burkinabè des Métaux Précieux (CBMP), the state marketing board in charge of buying all gold produced in the country, cleared the way for a growing dominance of national small- and middle-sized private companies (Côte, 2013; Werthmann, 2017). These companies could obtain permits from the Ministry of Mines and could control artisanal mineral production in limited areas under certain conditions.

While the mining acts offered instruments for artisanal miners to operate within the law, relations of production on the ground often looked different from those envisaged by legislators. Private companies obtained official permits to control production and sale, but in practice they acted merely as *comptoirs*, establishing control over the commercialization of gold, while leaving extraction and processing largely in the hands of self-organized teams of diggers and informal processing entrepreneurs (di Balme and Lanzano, 2013; Côte and Korf, 2018). Competition became fierce, with most gold-rich regions of the country not only being targeted by foreign junior companies, but also by artisanal mining companies. By the early 2010s, the ASGM sector was dominated by a handful of private companies, which tried to consolidate their position by accumulating different types of permits through the actions of subsidiaries and strawmen (cf. Luning, 2020). Competition over available land made this system increasingly less viable. An additional threat came from the political turmoil experienced by the country, when the 27-year-old regime led by Blaise Compaoré was overturned by a popular uprising in October 2014. Two years later, a parliamentary committee investigated crimes in the mining sector, exposing illicit practices in ASGM and abuses committed by private *comptoirs* (Assemblée Nationale du Burkina Faso, 2016; cf. Werthmann, 2017). Today, while private *comptoirs* are still active, their influence and territorial control has diminished considerably, to the benefit of local informal committees that have replaced some of their functions. Meanwhile, the government has formed a national agency to explore options for formalizing of ASGM. While this development is often interpreted as a move back to a model of state control over artisanal gold production and commercialization, attempts to formalize the sector are likely to encounter many obstacles in practice (Konkobo and Sawadogo, 2020; Medinilla et al., 2020). General recent developments in the Sahel, with mounting insecurity and the proliferation of non-state groups and violent incidents in mining regions (International Crisis Group, 2019), are an additional source of concern (see also Lanzano, Luning and Ouédraogo, forthcoming).

### 5.2. Cyanidation, conflicts around ownership and the decline of 'comptoirs'

In this historical path, where different governance patterns succeeded one another, socio-technical innovation—and particularly the shift from mercury to cyanide processing—played an important role. While it is difficult to trace the exact trajectories of the arrival and diffusion of cyanidation in ASGM in Burkina Faso, its presence was confirmed by the early 2010s. At that time, most ASGM operations revolved around mercury-based processing, with mechanical grinding and "washing" through sluice boxes performed on the ore extracted in the shafts. As a chemical substance, mercury was at the center not only of material production, but also of the political debate about environmental risks associated with the sector. Basic cyanidation techniques could be performed on the final residues—called *garga* or *nyeka* ('mud' in the Mooré language)—accumulated after processing with mercury: this usually happened far away from the mining sites, in areas with restricted access (Lanzano and di Balme, 2021). The private *comptoirs* that dominated the ASGM arena controlled most of these areas, sometimes informally and sometimes through official permits for semi-mechanized mining. The *comptoirs* used their networks and connections to keep a hold of the necessary inputs and knowledge, and thus acted as gatekeepers.

Progressively, cyanide-based processing became a source of disputes. In the years 2013–2015, the Burkinabe press started to report cases of conflicts involving owners of private *comptoirs* and informal processing entrepreneurs (e.g., Kiemtoré, 2013; Ouédraogo, 2015). Most of the latter were women who had been able to thrive on the business of washing ores and selling residues for reprocessing (Ouédraogo, 2020). Conflicts concerned the ownership of these residues and the conditions under which they were sold to outsiders (who would then submit them to cyanidation) (Lanzano and di Balme, 2021). While private *comptoirs* claimed an exclusive property of the 'muds', many miners and processing entrepreneurs resisted these claims, determined to maintain control over each by-product of the processing chain, and to stick to previously existing informal trading practices. These conflicts, which in some cases led to court trials, made it clear that cyanide was assuming a central role in the organization of production. Even if mercury was still employed at earlier stages of processing, cyanidation became an essential factor in determining the value of the different by-products of the production chain. In a context of increasing competition for space and for permits, declining gold prices (after 2012), and increasing scarcity (of easily accessible deposits), the intensification made possible by cyanidation seemed an attractive option for all actors involved. This evolution radically questioned the hybrid governance model that had been able to marry, up to that point, corporate profits with the livelihoods of less powerful and often informal actors.

While some of the *comptoirs* initially won the court cases concerning their new claims, in general terms their position weakened. On the one hand, pressure from industrial mining companies operating in the same areas grew considerably. On the other hand, informal miners and processing entrepreneurs resisted their efforts to tighten control over production by relocating to areas outside the influence of the *comptoirs*. The partial decline of private *comptoirs* since at least 2015 went hand in hand with a transition to cyanidation as the main processing method and source of profit. This can probably be explained by the *comptoirs*' diminishing presence on the ground, and their consequent inability to restrict access to 'new' processing techniques. Being able to escape or circumvent the control previously exerted on them, cyanide technicians started to bring their expertise to other mining areas.

In the last few years, rudimentary cyanidation plants appeared in most ASGM sites, usually set up by local mining sponsors and experienced miners reinvesting some of their gains from earlier activities. These generally consist of fenced fields, where ponds dug in the ground are used for decantation of the 'muds' immersed in solutions of water and cyanide. The result of the leaching process is left to drip in smaller central ponds, where it is collected in U-shaped plastic tubes and mixed together with zinc dust. The final result is then mixed with other chemical products—mostly sulfuric and nitric acid—and is 'cooked' by miners on charcoal stoves in the open. Alternative methods of post-leaching processing, based on activated carbon, have made their first appearance in very recent times (after 2017–8).

In most mining sites, cyanidation areas include several similar ponds located at small distance from each other, belonging to different owners. Sometimes, these are specialized operators that process other miners' ore in exchange for a compensation, or buy ore from others to process. In other cases, miners owning extraction pits or active in other stages of production also invest in cyanidation plants to be able to process the ore that they extracted.

### 5.3. Filling the void: vertical integration and the shift towards cash

In this latest phase, technological and institutional innovation appear to proceed together. In many cases, the power vacuum left behind by the *comptoirs* was filled by informal committees, often composed of local personalities and experienced miners. These committees assumed some of the functions—coordination, but also price fixation, gatekeeping or informal taxation—that were previously performed by the *comptoirs*. While committees, and other informal leadership structures of this kind, generally enjoyed recognition at the local level, they could not claim a formal status or pursue legal action to the same extent that the *comptoirs* did. Their methods to secure consensus among miners had to be 'softer'. Yet, prices at which residues should be sold, or individual operators' freedom to choose their own clients, remained contentious issues, especially now that mining was undergoing a cyanide revolution.

At the same time, the centrality assumed by cyanidation determined new dynamics in the relations and transactions within the production chain (see Lanzano and di Balme, 2021). With most of the profit now realized at the end of the chain, i.e., after the final residues have undergone cyanidation, mercury-based processing has become comparatively less attractive. While still practiced, it is now seen as relatively marginal. Miners and processors, especially the wealthiest and most powerful, strive to retain control over the entire process in order to submit all their gold ore to cyanidation. Incentives to minimize transaction costs and to integrate the different steps of production for the sake of scale economies have thus multiplied, producing an informal process of vertical integration (at a different scale but similar to the one imagined by Williamson, 1971). In practice, this meant that many informal entrepreneurs previously specialized in one single activity—for example, the financial sponsors or leaders of a mining team, or the owners of a washing stall or a cyanidation plant—invested in internalizing most or all phases of production within a single economic enterprise. Many mining sites are now marked by a competition between parallel informal businesses, each of which oversee a complete production chain, from the extraction of gold ore in the shafts, through crushing and washing, to final cyanidation performed on the *nyeka*. Even if the *comptoirs* have lost most of their influence, power has concentrated anew, this time in the hands of miners and sponsors who possess more capital to invest or have wider networks to rely upon. While the extent of technological innovation and capital concentration remain more limited compared to the cases of the Philippines and Indonesia, entry barriers for new investors are likely to rise, and the process of marginalization of certain actors, e.g., the women processors, will not necessarily be reversed.

In this context, a progressive shift from in-kind remuneration and equal sharing of the ore after extraction, toward cash remuneration and profit-sharing after cyanidation, has also been observed (Lanzano, 2020).[7] A complex combination of mutual trust and profit-oriented strategies used to inspire working and sharing practices among miners, balancing out incentives for teamwork and for individual monetary gain. In that model, receiving compensation in kind—and more specifically, in shares of unprocessed gold ore—symbolized the participation, even if from unequal positions, in a shared enterprise. The shift to cyanidation will likely affect not only the mechanisms of creation and distribution of value along the production chain, but also miners' subjectivities and identities.

It is still too early to say if these trends represent a mere adaptation of pre-existing patterns to a new technological landscape, or a transition towards waged work and more structural inequalities. As resource depletion looms in many artisanal mining areas, cyanidation has represented a tool to intensify the extraction of value and to readapt mining practices to the incoming bust phase. In short, under the influence of technological change and decreasing reserves, the egalitarian and risk-prone ethos for which *orpaillage* became famous in the first boom phases (see for ex. Grätz, 2009) may experience profound transformations.

## 6. Conclusion and policy implications

In all three countries, cyanidation is rapidly changing the face of ASGM, just as it changed the face and fate of industrial gold mining in the twentieth century. In table 1, we summarize the key findings emerging from each of the case studies in relation to four variables: timing (when did cyanidation first emerge and when did it expand?), type of cyanidation methods used, ownership structures, and key social impacts.

While the impacts of cyanidation vary across cases, a number of cross-cutting findings emerge. Due to dramatic improvements in value-to-volume ratios, ASGM is no longer limited to easily accessible and high-grade deposits, but can target more complex and lower-grade deposits. Moreover, cyanidation has transformed previously worthless tailings into a precious resource. In Burkina Faso and Indonesia, a wide range of actors became involved in the trade and the processing of tailings. In the Philippines, where cyanidation was introduced as early as the 1980s, access to the tailings trade and to processing activities has always been more constrained.

At the same time, our exploratory analysis indicates that the advent of cyanidation and the evolution towards more advanced operations may contribute to exclusionary tendencies within ASGM. To the extent that this issue has received attention in earlier research, the focus was on how the owners of cyanidation facilities are 'exploiting' artisanal miners (e.g. Veiga et al., 2014; Bansah et al., 2018). Our findings suggest that dynamics of inclusion and exclusion are much more complex, and require an understanding of the intricate linkages between mining, processing, labor arrangements and revenue-sharing schemes. In the Philippines and Indonesia, we seem to be witnessing a transition from revenue-sharing towards casualized and wage-like labor arrangements. Even in Burkina Faso, where the advent of cyanidation facilitated the emancipation of miners and processing entrepreneurs from the private *comptoirs*, new arrangements similarly embody exclusionary traits. In all

[7] Unlike the Indonesian case, in the mining sites observed in Burkina Faso remuneration is still proportional to the profit made from each batch. It is not conceptualized as a wage, although miners seem to fear an increased discretionary power of business owners in defining a "pay" level that could not reflect the real profits.

**Table 1**
Key findings from the case studies.

| | Philippines | Indonesia | Burkina Faso |
|---|---|---|---|
| **Timing** | Started as early as 1980s, but became widespread starting late 2000s. | In use since at least 2001 in North Sulawesi, spreading to West Java around 2007, and thereafter becoming common nationwide. | Limited use as early as the mid- to late 2000s. Gradual diffusion in early 2010s, acceleration after 2013–4. |
| **Methods** | Vat leaching in tanks of different sizes. Heap leaching can also be found in some parts of the country (notably in the North). | Carbon-in-leach processing, either in large cylindrical tanks (*tong*) or in tarp-lined pools (*rendaman*). | Basic ponds dug in the ground used for leaching and zinc precipitation. Other chemical products—mostly sulfuric and nitric acid—are also used. The result is 'cooked' by miners on charcoal stoves. After 2017–8, other methods of post-leaching processing (activated carbon) have appeared. |
| **Ownership structures** | CIP plants require significant investments. Typically owned by big financiers, local politicians, or any combination of those. | Cyanidation facilities vary in scale and cost, however most plants are owned by local elites and wealthier miners. Non-owners may 'rent' cyanidation equipment or sell tailings to plant owners. Poorer miners have limited access. | Before 2013–4, fewer plants controlled by private concessionaires (*comptoirs*). In recent years, several cyanidation facilities in each mining site owned by different operators. Ore belongs to (or is bought by) the owner of each pond, or can be processed in exchange for payment. |
| **Key social impacts** | Contributed to further expansion of ASGM, including emergence of new and more unequal revenue-sharing systems, and apparent trend towards wage labor. | Created a market for ASGM tailings, resulting in new income opportunities. However, most benefits accrue to local elites who own cyanidation equipment. Gold production processes are increasingly consolidated and wage-like labor is more common. | Initially conflicts between *comptoirs* and informal miners, often leading to marginalization of certain actors (notably women processors). With the decline of the *comptoirs* access became more equitable, but cyanidation was accompanied by trend toward concentration of power, and "vertical integration" of the different stages of production. |

three cases, cyanidation fits in with a broader trend towards vertical integration and consolidation in the value chain, whereby a limited number of actors with access to capital (and in some cases to political power) succeed in capturing most of the value added by cyanidation. Poorer miners and laborers, meanwhile, can only gain access to these benefits by accepting partial losses in the forms of milling fees, transaction costs, or worsening labor terms. These findings suggest that the spread of cyanidation risks undermining some of the 'democratizing trends' that have been attributed to ASGM (Bryceson et al., 2013). Instead of offering accessible livelihoods and opportunities for upward social mobility to miners, it may reinforce inequalities and raise barriers to entry.

These insights harbor important lessons for the widening range of efforts on the part of governments, international organizations, and civil society organizations, to promote the use of clean and efficient technology in ASGM. First, policymakers should be wary of treating cyanidation as a viable, cleaner alternative to mercury amalgamation. In the three cases described here, cyanidation complements rather than replaces mercury amalgamation. As Spiegel et al. (2018) argue, cyanide-based tailings reprocessing needs inefficient mercury processing, and vested interests in the processing industry could actually be an impediment to eradicating mercury use. Secondly, as illustrated particularly by the Philippines and Indonesia cases, the continued use of mercury may be a part and parcel of weaker actors' strategies to maintain a foothold in an increasingly capital-intensive and exclusionary ASGM economy. Existing initiatives aimed at managing cyanide use in gold mining, such as the Cyanide Code or the Minamata Convention (a multilateral treaty focused on reducing global mercury emissions, which includes a note about eliminating cyanide use when paired with mercury in ASGM processing), tend to neglect these uneven social dynamics while focusing on environmental and public health goals. Moreover, certification schemes like the Cyanide Code are designed for legally recognized mining operations (see Nyanza et al., 2017), whereas most ASGM sites worldwide, and all of the cases described here, remain informal. While environmental concerns associated with cyanide—which is both toxic and magnifies the danger of mercury—are warranted, our cases demonstrate that management endeavors must also account for cyanide's social consequences. More broadly, the case studies in this article indicate that the adoption and diffusion of a new technology—such as cyanidation—is not merely a matter of rational choice and increased efficiency (see also Pfaffenberger, 1992). Rather, it is a complex social phenomenon embedded in power relations and reflecting underlying socio-institutional arrangements (Smith, 2019; Verbrugge and Geenen, 2020). In both Burkina Faso and the Philippines, different actors use or have used, at least temporarily, their political and legal power to maintain a relative monopoly on cyanide-based processing. In short, our analysis indicates that any effort to change the technological set-up of ASGM needs to consider how it may *differentially* affect the actors involved.

## CRediT authorship contribution statement

**Boris Verbrugge:** Conceptualization, Investigation, Writing – review & editing. **Cristiano Lanzano:** Conceptualization, Investigation. **Matthew Libassi:** Conceptualization, Investigation.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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