

PRICE VOLATILITY AND PRICE RISK IN THE ARTISANAL AND SMALL-SCALE MINING INDUSTRY

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1. Introduction

Artisanal and Small-scale Mining (ASM) activities form a major source of income for a very large number of households in developing countries. Artisanal mining is unpleasant and laborious. Consequently, almost all artisanal miners are driven to this activity through poverty. Their legal rights to the deposits they mine are often at best ill-defined. Employees in small scale mines are generally slightly better off in terms of wages, working conditions and non-wage benefits, such as pension and other social security provisions. Legal rights may be better defined. Whilst both types of mining have the potential to alleviate poverty, even if in a small way, ASM activities often raise serious environmental concerns, as when mercury is used to leach gold.

Much of the academic discussion of the ASM sector has rightly emphasized legal, health, safety and environmental issues. Less attention has been paid to the livelihood impacts of these activities. Hilson (2006) wrote: "Prolonged neglect of the sector's poverty and broader socioeconomic issues has ... rendered promising policy and support initiatives ineffective." He goes on to argue that the relationship between poverty and the ASM sector is more complex than is generally admitted. These issues therefore merit greater attention both from the academic and policy communities.

Beinhoff (2002) reported that up to 12% of metallic minerals, 31% industrial minerals, 20% coal, 10% diamonds and 75% of gemstones production come from ASM operations.¹ According to Hruschka and Echavarria (2011), 25 million people may work as artisanal miners, perhaps one in forty of the "bottom billion". No-one compels this activity so, for an economist there must be a presumption that mining makes them better off, or at least, that they expect that it will do so. (Of course, if they were less poor, they might seek more palatable ways to sustain their livelihoods). This paper examines how artisanal and small scale mining can contribute to the maintenance of rural livelihoods.

The paper focuses on price trends and price volatility over the period since 2000. The decade long metals price boom, termed by some as a super-cycle, which started in 2004 and is starting to fade only in 2013, has resulted in mining becoming the most important economic activity in many poorer, non-oil producing developing countries. This is true both

¹ No source is provided for these estimates.

of the formal and informal mining sectors. Metals and gemstone prices have generally risen by more than agricultural prices thereby increasing the attractiveness of the ASM sector – see section 6. At the same time, metals price volatility has also increased, again generally by more than the volatility of relevant agricultural crops – see section 7. While price volatility is generally seen as injurious to producers, here it is argued that many artisanal miners are in a position to benefit from higher price volatility.

The structure of the paper is as follows: Section 2 starts by characterizing the ASM sector and distinguishing between small scale and artisanal operations. Section 3 documents the relative importance of different metals and gemstones in the ASM sector. In section 4, some common features of artisanal mining and small scale agriculture are noted. This leads into section 5 which looks at price risk. In Sections 6 and 7 the price and volatility trends are documented, respectively, in the sector. Section 8 looks at the pass-through of international into domestic prices. In section 9 the comovement of ASM metals and gemstone prices with relevant agricultural prices is detailed. Section 10 concludes.

2. The artisanal and small scale mining sector

The distinction between artisanal and small scale mining is standard despite the fact that the two forms of activity tend to merge into each other. Hentschel *et al.* (2002) formulate a long list of characteristics of the artisanal and small scale sector. Informal artisanal and more formal small scale mines operate on the same or contiguous deposits, and individuals often shift between artisanal mining and employment in a more formal small scale mine in the same vicinity. In certain cases, operators of small scale mines may sub-contract extraction to individual miners or groups of miners so that the mine is effectively operated on an artisanal basis despite its formal structure. Enterprises may be formal by some definitions (e.g. registration) but informal in others (e.g. tax payment).

In this paper, artisanal mining refers to mining activity undertaken by individuals or small groups of workers (often family groups or neighbours). Typically, these groups have no formal association. They may also be fluid in the sense of lacking fixed membership. Lacking formal structure, they are almost inevitably in the informal sector of the economy. The groups may also be itinerant, either within the area in which the group resides or over a much wider area. In many cases, including most of the itinerant cases, the miners lack

licences or other formal permissions for the land they mine. Given these characteristics, it is almost inevitable that artisanal mining exhibits very low levels of mechanization. By contrast, significant capital expenditures presuppose an ownership structure, or, in the case of leasing, a legal identity.

The term small scale mining generally refers to mining organizations which do have some formal structure but which operate with relatively low levels of capital. Because mining generally offers relatively limited opportunities for substituting labour for capital, limited capital typically implies low output. However, the existence of a formal structure implies that these organizations are more likely to be integrated at least to some extent into the formal economy, for example through payment of tax and pension contributions, and are likely to have mining licences or other permissions.

Hruschka and Echavarria (2011) document four types of artisanal mining group:

- a) Permanent artisanal mining. This group of artisanal miners is involved in mining on a year-round basis. Mine revenues therefore form their basis for subsistence.
- b) Seasonal artisanal mining. This group alternates between mining and agriculture depending on the season (for example, mining in the dry season) and perhaps on likely returns.
- c) Rush artisanal mining. New discoveries or substantial price increases can generate a rush of artisanal and other informal miners attempting to make quick speculative profits.
- d) Shock-push artisanal mining. This group of miners is “pushed” into artisanal mining as the result of shocks in other sectors (conflicts, natural disasters or exceptionally low prices). The presumption is that their involvement in the sector is transient but they may become trapped into becoming artisanal miners over the long term.

The relative importance of these four groups will vary over country and time. It is useful to add a fifth type of artisanal miner to this list:

- e) Immigrant miners. The high metal price decade starting in 2004 has seen the establishment of many Chinese mining companies throughout the developing world. Many of these bring their own workers, not all of whom remain with the small or

medium scale mining company which brought them into the country. This has resulted in a new group of non-indigenous artisanal miner, often with more capital than local artisanal miners but also often with even less legal title to the mines they operate.

The viability of small scale mining depends on both geological and technological features – in the case of gemstones, how they crop,² and, in that case of metals, how easy it is to separate the metal from the ore. These factors differ across metals and minerals and also across geographical locations.

There are three principal mining techniques: opencast, underground (which includes shallow and deep mining) and alluvial mining. Economies of scale are most pronounced in opencast mining and least important in alluvial mining (with the exception of sea-bed mining). Capital costs tend to be highest in opencast and deep mining. It is difficult for small scale mines to compete effectively in industries in which economies of scale are pronounced and capital requirements high. For these reasons, small scale mining is now the exception in most base metal industries despite the fact that some of these metals have been mined on a small scale for many centuries. Alluvial extraction of gold and tin remains an important sphere of artisanal and small scale mining.

Small scale extraction is important for many gemstones. They differ from most metals in that the rough gems are obtained without intermediate processing (smelting, refining etc.), although the same is also true of gold. Diamonds occur alluvially facilitating small scale operations, as well as in pipes, which require underground mining typically be undertaken by medium or large scale enterprises. Many coloured gemstones, such as emeralds, rubies, sapphires and tanzanite, occur in insufficient abundance to justify large scale exploitation.

An important distinction is between metals and minerals mined for the international market and those mined for domestic consumption. Trade barriers and transport costs allow prices to differ across and (in the case of transport costs) within countries. For metals which enter world trade, transport can be a major cost component where the distance to the port is long. Transport costs are also particularly important for heavy but low value products such as aggregates, but also to a lesser extent for coal and iron ore. These costs can imply that

² In geology, the verb “to crop” means to come to the surface,

small scale activities which may be economically viable in one country or region are not viable in another. In these low value-to-weight metals, small scale miners may be able to compete with the mining majors in their local or domestic markets since market proximity outweighs the lower scale-based production costs of the majors. The Chinese iron ore mining industry is one important example. The resulting industries can contribute significantly to economic activity despite the small scale of the individual enterprises. They have been relatively lightly documented and researched and there is little information on prices at which domestically traded minerals are sold. For this reason, the main focus of this paper is metals and gemstones which enter international trade.

3. The importance of different metals and gemstones

It is important to have some idea of the relative importance of different metals and gemstones in the small scale mining sector. Because these activities are, at best, only partially recorded by national statistical agencies any such estimates are necessarily impressionistic and perhaps for this reason, authors have shied away from such attempts. Defining the ASM sector as comprising all mines with 100,000 (short) tons per year output,³ Noetstaller (1987) estimated the 1983 value share of the sector as approximately 16% of total mine output. This share included both metals and industrial minerals but excluded gemstones. This value share can be broken down as approximately 11% for metals and 25% for industrial minerals. He also reported value shares of approximately 10% for diamonds and 75% for semi-precious stones.

Noetstaller's estimates drew on Carman (1985) who provided estimates of the value shares for specific metals. These estimates are reproduced here in Table 1. The numbers reported here exclude the production of industrial minerals which are generally seen as part of the construction rather than the mining industry (Hruschka and Echavarria, 2011). Iron ore was the single most important ASM metal followed by gold and copper. However, for each of these three metals, ASM production as a share of total world mine production remains in the 10% to 15% range. For some less important metals, in particular chromite and tungsten, the ASM sector contributed half or more of total production. Carman estimated that 100% of beryllium production, here included in the residual category, was from the ASM sector.

³ 907,000 (metric) tons per year.

These figures should be taken as approximate and, in any case, are now thirty years old, yet more recent estimates are unavailable. Neither Carman (1985) nor Noetstaller (1987) provide any national or regional breakdown for their estimates. This is potentially important because rapid economic growth over the intervening period, particularly in Asia, will have stimulated both additional ASM activity and also greater formalization possibly resulting in a significant number of ASM enterprises graduating out of the sector, often as the result of take-overs by larger scale mining companies.

Despite these qualifications, I take the estimates in Table 1 as guiding the choice of metals to be examined in looking at the impact of price volatility on the small scale mining sector. Appendix 1 lists the characteristics of the industries which produce the metals listed in Table 1 with particular reference to the ASM sector. The discussion extends to the diamond and coloured gemstone industries.

4. Artisanal mining and smallholder agriculture

In what follows it will be valuable to distinguish between two archetypal types of enterprise. A small scale miner is characterized as a formal sector enterprise possessing a licence or other permission to mine which can commit a limited amount of capital and which may use some paid labour. Income from the mine is likely to be the principal or only source of income for the mine operator. By contrast, artisanal miners are characterized as informal enterprises of individuals, families or groups of miners who operate without formal licences or permission and, as a result, are not committed to particular locations and may therefore move between sites. Their capital will be limited to what they can carry. They may mine on a seasonal or opportunistic basis and, in the important case of seasonal mining, will rely primarily on agricultural income for the major part of their consumption.

The small scale mining sector is typically considered as a poor relative of large scale mining. Artisanal mining, on the other hand, is often better seen as a close cousin of smallholder agriculture. The two sectors face common problems of price and yield risk, limited access to credit (and hence capital), uncertain title and poor representation in and access to government. Seasonal artisanal households will rely on earnings from both sectors either as the result of a seasonal division of working time between mining and agriculture. Some

permanent artisanal miners may be members of farm households some of whose members are involved in agriculture and others in mining.

Just as there are geological and technological differences between mining different metals or minerals, there are agronomic differences across crops. Some crops, like cocoa, which permit intercropping, are better suited to smallholder than estate production. There are few benefits to scale. A second group of crops, like natural rubber, are well-suited to estate production and demonstrate scale economies – intercropping is not desirable and a single rubber tapper can cover a large area. Finally, there are crops which are intermediate, like coffee, where smallholders and estates can compete on broadly equal terms. We are therefore able to observe the same sorts of variation of enterprise size and organizational structure in developing country agriculture as in mining, except that there are few agricultural plantations of comparable size to the largest mines.

5. Price risk

Miners, like smallholder farmers, are subject to price risk when they need to commit resources (labour time or physical inputs) prior to knowing what price they will receive for the resulting output. Price risk has received a large amount of attention in both the academic and policy literature relating agricultural export crops, such as cocoa and coffee – see, for example, Newbery and Stiglitz (1981), Dana and Gilbert (2008) and Gilbert and Morgan (2012), but relatively little attention in metals markets⁴ and virtually none in relation to gemstones.

The agricultural literature has emphasized the uncertainty costs associated with revenue variability. These costs arise because low farm revenues translate directly into low household consumption. In particular in Africa, poor households have little access to formal banking. When revenues are high, households invest in buildings, for example by investing in a cement floor or corrugated iron roof for their houses. Such housing investments cannot easily be realized to sustain consumption levels in subsequent times of revenue shortfalls and the absence of rural banking implies that any loans must be from informal sources (wider family, neighbours or money lenders). The small scale mining and artisanal sector will

⁴ Brunetti and Gilbert (1995) discussed the volatility of non-ferrous metals prices.

experience the same problems, not least because of the overlap between participation in the two sectors.

It is less widely appreciated that price variability also generates opportunities which arise because those involved in the industry can vary their inputs, in particular their time input, according to whether output prices are high or low (Oi, 1961). Rush miners are evidently attracted by the prospect of getting rich, or at least of generating sufficient money to escape poverty. However, the possibility of profiting from high prices is more general than this and is due to the fact that artisanal miners do not make contractual or capital commitments.

When producers are involved in producing two distinct products, price variability makes diversification attractive, in particular when price movements exhibit low correlations. This is typically the case if one examines mineral and agricultural food crop prices since food prices are, to a large extent, driven by weather shocks which have little or no impact on the prices of mineral products. The very fact that artisanal miners have little or no physical capital implies low fixed costs and hence low opportunity costs of moving in or out of the industry. In particular, they can switch their labour time between agriculture and the artisanal mining sector. This is most evidently true of seasonal miners but is also valid to some extent for permanent miners who may grow subsistence crops or who have the option of returning to their home village if mining becomes unattractive. Small scale enterprises in the formal sector have a greater commitment and thus are less able to shift between activities.

In Appendix 2, I set out a simple illustrative model of a small scale miner and an artisanal miner both facing the same price distribution. The small scale miner is entirely reliant on his mining income but has lower production costs than the artisanal miner, who has some income from agriculture. The model envisages production in two periods. The small scale miner needs to commit resources for the two periods. The artisanal miner can commit period by period and will not mine if the price is low. The small scale miner is always better off with low volatility. This is in line with standard theory set out for agricultural markets. However, the model demonstrates that, in the circumstance that changes in the miner's total income resulting from changes in metals price are small, the artisanal miner gains from

increased price volatility. This is because the “option value”⁵ of producing when prices are high is greater than he loses from the uncertainty associated with increased income variability.

The small scale mining sector is also subject to geological risk. This is akin to yield risk in agriculture. A mining entrepreneur has to commit resources prior to knowing precisely what the terrain the mine can yield. A small scale diamond miner may lease a stretch of gravel which, from the surface, looks identical to the neighbouring stretch leased by a competitor, but one will yield more diamonds than the other. Prior to digging a pit to mine copper ore, a miner will only know how the ore crops on and near the surface – he gets either a pleasant or an unpleasant surprise as he excavates. However, while individual small scale miners face substantial risks, this may be less evident at the level of national production – the production of diamonds is the same whichever of the two competitors has the luck or skill to lease the better gravel site. Furthermore, geological risk may be lower for illegal artisanal miners who, since they do not regard themselves as bound by the requirements of legal permissions, are free to move on without encumbrance. For miners in the unregulated illegal sector, health and safety risks are probably more important than price or geological risk.

It is difficult to assess the incidence of geological risk in small scale mining from publically available data. Section 7 looks specifically at price variability in those metal and gemstone commodities which are most important in the sector and asks whether this variability is a serious problem for those active in the sector. Throughout the section, parallels with smallholding agriculture are stressed. Secondly, correlations between price changes in the products of the small scale mining sector and those of marketed products produced in smallholder agriculture are examined.

6. Price developments

This section and Section 7, examine price and price volatility developments for the ten metals listed in Table 1 as the most important for the ASM sector, for diamonds and the three most important coloured gemstones and for a comparison group of eight agricultural

⁵ I use the term “option value” in a loose sense here. The effect should more correctly be seen as an application of the Oi (1961) result that producers can gain from price variability.

commodities which are important for developing country farmers. The sections also consider annual average U.S. dollar prices in world markets deflated by the U.S Producer Price Index (all items) so the deflated prices effectively measure prices relative to the general level of prices at the wholesale level. The period since 2004, over which time metals prices have boomed, is the specific focus.

The prices considered in the analysis have different reporting statuses. Eight of the twenty-two prices are exchange cash prices (cocoa, copper, gold, lead, maize, silver, tin and zinc). Commercial transactions prices will differ from these prices by variable premia depending on location and grade, and in any case most commercial transactions are made on the basis of nearby futures prices rather than cash prices. These differences will generally be small. The coffee price is an official price which averages nearby futures prices for two different types of coffee (mild Arabica and robusta). The remaining thirteen prices are for which there is no active futures exchange and where import unit values into U.S. or northern European ports are analyzed. In all cases, prices are on a c.i.f. basis and therefore over-estimate the price obtained by the exporter, and hence also by the producer.

Figure 1 plots the deflated U.S. dollar prices of the eight base metals over the two decades 1982-2011. The eight base metals prices move closely together. These real prices were broadly constant from 1982-2003 with a short upward burst in 1987-89. They then approximately doubled over the period 2004-06 and remained high until the end of the period under consideration. There are two exceptions:

- a) The real tin price fell dramatically with the 1985 breakdown of the International Tin Agreement (Gilbert, 1996). However, over the period since 2006 it has recovered to its pre-1986 real level as the metal has found new uses in the expanding microelectronics sector.
- b) Since 2008, the iron ore price has risen much more sharply than non-ferrous metals prices as the consequence of very strong demand growth for steel in the Chinese construction sector.

Figure 2 plots the deflated precious metals and gemstones prices over the same period. The period divides around 2005. Prior to 2005, a negative trend is apparent for the entire set of prices with the exception of diamond unit values which were broadly constant by the De

Beers-controlled distribution cartel.⁶ The ways part in 2005 with silver and gold prices moving sharply upwards while the gemstones show more variable and less dramatic movements – emerald and sapphire prices rising, rubies declining and diamonds volatile around a broadly constant level.

Overall, real prices for ASM metals and minerals have therefore risen over the past two decades although these rises have been stronger for metals more than for gemstones. The most dramatic rise documented in Figures 1 and 2 has been that of iron ore prices but it is unclear to what extent to which the world price of iron ore received by the major multinational exporters has translated into higher prices for small producers. The pass-through is probably good in major iron ore importing countries, and in particular China, but low in countries which are not involved in the international iron ore trade. By contrast, pass-through is probably superior for the non-ferrous metals and gemstones which have a high value-to-weight ratio – see section 8. Price developments in gemstones show greater variability than those in metals. Diamond prices have struggled in the face of the decline in the power of the De Beers cartel. A wide variety of different gemstones are produced in the ASM sector. The varied price developments in the more major gemstones whose unit values are graphed in Figure 2 suggests that the prices of these less important gemstones are also likely to have exhibited idiosyncratic behaviour.

Table 2 shows the increase in real prices US dollar prices of the principal ASM metals and gemstones comparing the eight years 2004-11, which coincide with the “super-cycle boom”, with the previous eight years 1996-2003. Both real non-ferrous metals and precious prices generally rose by over 200% over this period, while iron ore prices rose by nearly 400%. Gemstones performed less dramatically, rising by 120%. The most interesting comparison is, however, with the group of agricultural products (five food and three non-food commodities), the prices of which may be taken as proxying the likely prices artisan miners might have obtained through farming. Notoriously, agricultural food prices spiked in 2007-08 and again in 2010. However, that spike was more modest than the metals price rises.

⁶ See Roberts (2003) for a discussion. The cartel was effectively broken by the 2006 decision of the European Commission to prohibit the agreement by which De Beers had assumed responsibility for the international distribution and marketing of diamonds produced by the Russian company Alrosa, the second largest diamond mining company after De Beers itself.

Over the comparison period, real agricultural prices rose by 88% with very little variation within the group. This is less than half of the average increase in the metals prices. The implication is that the ASM sector became relatively as well as absolutely more attractive in the period from 2004.

7. Price variability

Commodity prices are variable because short-term production and consumption elasticities are low. Production responsiveness is low in metals because there is a lag of several months between mine production decisions and the sale of refined metal. Similarly, planting decisions in agriculture are made before new crop prices are known. In both cases, production decisions depend on expected prices, and not realized prices. Short-term demand elasticities are low because the actual commodity price may not be a large component of the overall value of the final product (tin in the price of mobile phones or cocoa in chocolate, to take two examples). Further, for those metals and agricultural products which are used in industrial applications, input choices and proportions are embodied in product designs and the specifications of the production processes.

Low elasticities determine the amplitude of fluctuations in commodity prices in conjunction with the incidence of shocks to production and consumption. Two types of shocks may be distinguished. Shocks to demand originating in the industrial business cycle predominantly affect industrial commodities, such as metals. Shocks to supply predominantly affect agricultural commodities. There is likely to be at most a low correlation between the two sets of shocks – see section 9. Low elasticities imply that small shocks to production or consumption can have a large impact on price.

The extent of price variability differs across commodities reflecting differences in industrial structure (competitive versus monopolistic or oligopolistic markets), the presence or absence of intervention schemes, the magnitude of the demand and (in competitive markets) supply elasticities and the magnitude of the shocks impacting production and consumption.

Volatility also varies over time and there is a widespread perception that volatility of primary prices has increased over the most recent years. Although this perception is

partially true, that judgement is too simple. Looking at food commodities, Gilbert and Morgan (2010, 2011) note that although price variability has been high in the period from 2007, it remains much lower than in the 1970s. Long period comparisons show a decline in volatilities. Shorter period comparisons may give different results. Gilbert (2012) shows that the volatility of grains and oilseed prices did increase over the period 2006-11 relative to 2000-06 but there were not significant changes in the volatilities of other food commodities. The volatility of crude oil prices has changed little over recent years (Gilbert and Mugeru, 2012).

In what follows, volatility is calculated as the standard deviation of logarithmic annual changes in deflated prices. This measure, which is the most widely used in the academic literature, is preferred to the alternative of standard deviations about trend because trend measurement can involve a degree of judgement. Table 3 reports the volatilities of the eight base metals prices charted in Figure 1, the gold and silver prices the four gemstone unit values charted in Figure 2 and, for comparison purposes, the prices of the eight smallholder agricultural crop prices considered in Table 2. In each case, volatility is measured over the periods 1983-2005 and 2006-11. The variance equality tests repeat those in Gilbert and Morgan (2010, 2011) and Gilbert (2012).⁷ The table also reports volatilities over the same periods for a number of smallholder crops.

We draw attention to three following features of these results:

- The volatilities of gold and silver prices are an order lower than those of other ASM metals and mineral prices and those of smallholder agricultural commodities. Furthermore, gold and silver volatility did not increase significantly in the period 2006-11.
- The volatilities of ASM base metals prices were very similar to those of smallholder agricultural crop prices until 2005 but the former increased sharply over the 2006-11 period while the agricultural price volatilities remained broadly constant.
- Up to 2005, diamond prices showed low volatility levels comparable to those for gold. With the breakdown of the De Beers cartel, diamond price volatility has

⁷ 1983 is the first year for which unit value data are available for ruby and sapphire prices while the split after 2005 is motivated by the discussions in section 5 and in Gilbert (2012).

increased dramatically. The volatilities of the less important gemstones are little changed.

- The volatilities of the comparison group of agricultural commodities shows very little change. This overall constancy hides a sharp jump in the volatility of rice prices offset by a large fall in coffee price volatility.⁸

I argued in section 5 that small scale miners will generally suffer from increases in the price volatility of their products while artisanal miners, particularly seasonal miners, may well benefit from increased volatility. The numbers displayed in Table 3 indicate that these effects may have been substantial.

8. Pass-through

The prices discussed in the previous sections relate to world markets. The pass-through issue concerns the extent to which movements in international prices are passed through to the producer prices paid in a particular sector. The volatility figures discussed above are only relevant to household decisions and welfare to the extent that the world prices, which formed the basis for those estimates, are transmitted into local markets.

Pass-through has been extensively examined for the smallholder agricultural sector – see Timmer *et al.* (1983), Ardeni (1989), Mundlak and Larson (1992) and a large subsequent literature but there does not appear to be any discussion of these issues for the ASM sector. It might be argued that the absence of extensive governmental involvement in ASM markets is likely to imply high pass-through. However, there is insufficient information about the marketing chain for ASM metals and gemstones to be able to make any statement regarding pass-through levels with confidence.

The over-riding conclusion from the agricultural pass-through literature is that the extent of pass-through varies by commodity and country and reflects institutional and legal arrangements which can change over time. The extent of pass-through depends on a number of features. Most obviously, international prices will only determine domestic prices to the extent that the commodity in question is exported (or imported). This will partly be

⁸ Gilbert and Morgan (2011) suggested that, while there has not been any general tendency for food price volatility to increase, there was evidence of an increase in the volatility of grains and vegetable oil prices – see also Gilbert and Morgan (2011).

determined by transportation and other costs, and partly by the presence or absence of export restrictions or taxes. In the ASM sector, metals and gemstones with high value to weight ratio will typically be traded, while aggregates and some other minerals with low value to weight ratios may be extracted solely or largely for domestic consumption. We should therefore expect to see high pass-through for the former group and zero or low pass-through for the latter. For example, in countries in which iron ore is produced solely for the local market, domestic prices may differ markedly from international prices. Where there is little or no pass-through, price variability at the international level has no implication for national price variability.

The second important determinant of pass-through is the extent of competition in intermediation. Where producers are faced with a large number of potential buyers, competition will force these buyers to offer keen prices. Where producers are faced with few alternative buyers, these buyers will be able to squeeze their purchase prices down to levels close to production costs. In that case, changes in world prices will primarily affect the profits of the intermediaries and pass-through will be low.

There are two preconditions for competition: free entry into intermediation and a sufficient number of producers to cover the costs of a large number of traders. The consequence is that the intensity of competition tends to be higher in zones in which producers are concentrated, and lower in small and isolated production zones.

Pass-through is also enhanced if producers are well-informed about the prices they can expect to obtain. This information is usually obtained from local newspapers or the radio. Producers will generally make it their business to be well informed about prices, but this process can be facilitated by good publicly-run price information systems.

Monopsony⁹ marketing boards form an alternative intermediation structure. Depending on how these boards are organized, they have the possibility of ensuring that producers are not exploited by intermediaries, although this is no guarantee that the price paid by the board will be generous. Pass-through depends on the extent to which the board changes its selling prices in relation to changes in world prices. In some cases, boards simply see themselves as providing efficient intermediation, while in other cases they attempt to smooth out

⁹ A monopsony market is one in which there is a single purchaser.

variations in world prices. Pass-through will be high in the former and low in the latter case. Where smuggling is possible (gemstones and precious metals), monopsony boards will be obliged to pay close to world prices – this will be the normal case in much of the ASM sector.

The following considers pass-through in the Ghanaian small scale mining sector where gold and diamonds are sold through the Precious Minerals Marketing Corporation (PMMC) which acts as a monopsony buyer for the sector. Miners have the option either of selling directly to the PMMC in Accra, or of selling to agents (Licensed Buying Agents or LBAs) who in turn sell to the PMMC. The PMMC buys gold at 2% under London prices, converted into cedis. This implies full pass-through at least down to the LBAs. In diamonds, the PMMC operates through a set of Licensed Buying Companies (LBCs) who sell the diamonds on the world market (typically in Antwerp) through affiliates. The LBCs negotiate the prices they pay LBAs or miners, and obtain a margin relative to the prices they achieve in Antwerp or elsewhere. Payment, however, is made through the PMMC which operates the fiction of being the monopoly seller. There is a large number of LBCs so competition should again ensure a good pass-through.

Figure 3 plots the PMMC gold price against the world price. The fit is almost exact. This is confirmed by regression of Ghanaian log price changes on U.S. log price changes which gives a slope coefficient which does not differ significantly from unity. Diamonds are heterogeneous and diamonds of different qualities fetch different prices. Ghanaian diamonds are small, usually less than one carat (“Indian goods”) and prices in that range are more consistent. Figure 4 charts the average price realized by PMMC for Ghanaian ASM diamonds against a weighted average of U.S. diamond import unit values with weights generated by a preliminary regression. PMMC prices are more variable than the US index and the implied pass-through coefficient, obtained from a regression of Ghanaian log price changes on U.S. log price changes, is 148%. In summary, in Ghana there appears to be full pass-through of world prices to the small scale mining sector. This contrasts with smallholder agriculture where pass-through is often very partial.

The ASM sector in Ghana is tightly and, apparently, well organized. It is also relatively well documented – see, for example, Hilson (2002) and Amankwah and Anim-Sackey (2003).

Further research is required to understand whether these results can be paralleled in other countries with important small scale mining sectors.

9. Comovement

Many artisanal miners divide their labour time between mining and agricultural activities. This may reflect the seasonal nature of agricultural production, as when some Ghanaian cocoa farmers transfer their entire activity to artisanal gold mining in the off-season when the cocoa trees do not require attention. Workers in small scale mines may be members of farm households, as when young men are sent to work in the mining sector leaving the women and older men on the farm. That tendency may be encouraged in areas, such as East Africa, where horticulture has traditionally been regarded as a female activity.

Diversification of this sort is risk-reducing even if it is not necessarily undertaken for that reason. Over the entire period under consideration, 1983-2011, and if there had been full pass-through,¹⁰ a cocoa-farming Ghanaian household obtaining one third of its earnings from ASM gold, would have experienced price volatility of 14.0% against a volatility of 18.7% if it had been entirely dependent on cocoa.

The extent of risk reduction obtained through diversification depends on the return correlation. If a household divides its activities equally between an agricultural crop commodity and an ASM metal or mineral with the same price volatility, the volatility of the diversified income stream falls to a fraction $\frac{1}{2}(1+r^2)$ of the original volatility where r is the correlation between the two sets of price returns. If the two returns streams are uncorrelated, this amounts to a halving of the volatility while if the correlation were negative, so that one activity provided insurance against the other, the volatility would be even greater.

Table 4 shows the correlations between the ASM metals and minerals discussed in section 4 and the six agricultural commodities taken as comparators over the entire period under consideration, 1983-2011. This in principle entails a total of 231 correlations, which would make interpretation difficult. I have, therefore, averaged the correlations across four

¹⁰ The pass-through assumption is realistic for gold – see section 8 – but not for cocoa where prices have been set by the Cocoa Board (Cocobod).

groups: non-ferrous metals, iron ore, precious metals, gemstones and agricultural commodities. The off-diagonal entries in the table show the average correlations between the various groups of ASM metals and minerals. The diagonal entries show the average correlations within each group (excluding the unit correlation of each return with itself).

The reported correlations of ASM metals and gemstones with agricultural prices are small and that with precious metals is negligible, the single exception being precious metals where the correlation is modest. The implication is that as in the cocoa-gold example set out above, households which divide their labour time between agriculture and ASM activities can substantially reduce their income risk.

10. Conclusions

The analysis in this paper has looked at the metals and gemstones which are most important in the small scale and artisanal mining sector. The existing literature has predominantly focused on legal, health and safety and environmental aspects of the sector. These are important issues and it is not my intention to detract from that discussion. Much less attention has been devoted to the livelihood impacts of small scale mining. The objective of this paper has been to set out some of these issues.

Two important issues have emerged in this discussion. The first of these is the commonality of the problems that arise in artisanal mining and smallholder agriculture, principally lack of access to credit markets and hence lack of capital. Many households involved in artisanal mining have their primary activities in agriculture – they either mine on a seasonal basis when farms require little attention or there is a division of household personnel between farming and mining. This obvious connection has tended to be overlooked because smallholder agriculture and small scale mining are discussed in different academic literatures.

The agricultural literature includes substantial discussion of the impacts of price volatility on poor farm households with limited access to credit. Price stabilization schemes have been implemented both at the national and international level with varying degrees of success to mitigate the impacts of agricultural price volatility. Farmers protect themselves from adverse price movements by diversification. The literature focuses on diversification across

crops. However, the generally low correlation between agricultural prices and the prices of metals and minerals indicates that diversification between agriculture and mining can be even more effective in limiting the impacts of agricultural price volatility.

The adverse impacts of price volatility arise in large measure because resources are committed prior to the revelation of output prices. Small scale mining enterprises need to expend money on mining licences and capital without knowing what quantities of metal or gemstones they will obtain or the prices these will achieve. Smallholder farmers plant crops and commit inputs prior to knowing harvest prices. Artisanal miners are in a different situation. They are free to mine or work on the farm on an opportunistic basis depending on the relative attractiveness of the expected prices. Since they have not committed resources to mining, they will tend to move in and out of mining depending on the metal or gemstone price. The paper demonstrates that, when the value of their mine output is small relative to that of their farm production, this option value of producing when prices are favourable will outweigh the adverse uncertainty impact of the metal or mineral price volatility. This conclusion reinforces the previous conclusion that diversification into artisanal mining can enhance the livelihoods of smallholder farmers.

The paper has also pointed to a lack of information on the artisanal and smallholder mining sector. The most recent comprehensive estimates of the size and importance of the sector appear to be those made nearly thirty years ago by Carman (1985). The metals price boom over the decade from 2010 will have enhanced the importance of the sector. It is desirable the governments and development agencies collect and collate more current and more disaggregated estimates of output and employment if we are to accurately evaluate the importance of the sector and the potential benefits that may result from an improved policy environment, including improved health and safety and environmental policies. Overall, price metals rises over the decade from 2010 exceeded those in smallholder agriculture. It would be interesting to know to what extent households have reallocated time to mining and away from agriculture.

The tight markets which resulted in high real prices for major metals also increased volatilities. Prior to around 2005, the volatility of non-ferrous metals prices was of the same order of magnitude to that of smallholder agricultural crops but since the mid-decade

metals price volatility has increased substantially while agricultural price volatility has changed less. Volatility levels for precious metals remain low. The breakdown of the De Beers diamond distribution cartel resulted in a sharp rise in the volatility of diamond prices but volatility levels tended to decline for coloured gemstones.

Price pass-through is another important issue on which we have little relevant information despite the large body of research in pass-through to smallholder agriculture. The price volatility estimates reported in this paper are only of policy relevance if the prices obtained by the miners themselves move in line with international prices. We have provided estimates for Ghanaian gold and diamonds which suggests that this is indeed the case in Ghana but we have no evidence on whether or not this result will generalize elsewhere.

The analysis in this paper has been conducted using data available from public sources. The paper has raised the important question of the impact of small scale and artisanal mining on the livelihoods of rural households in developing countries. It has suggested some preliminary answers. If the discussion is to be advanced further, this will be on the basis of household survey data which focuses on the extent to which households divide their labour time between agricultural and mining activities.

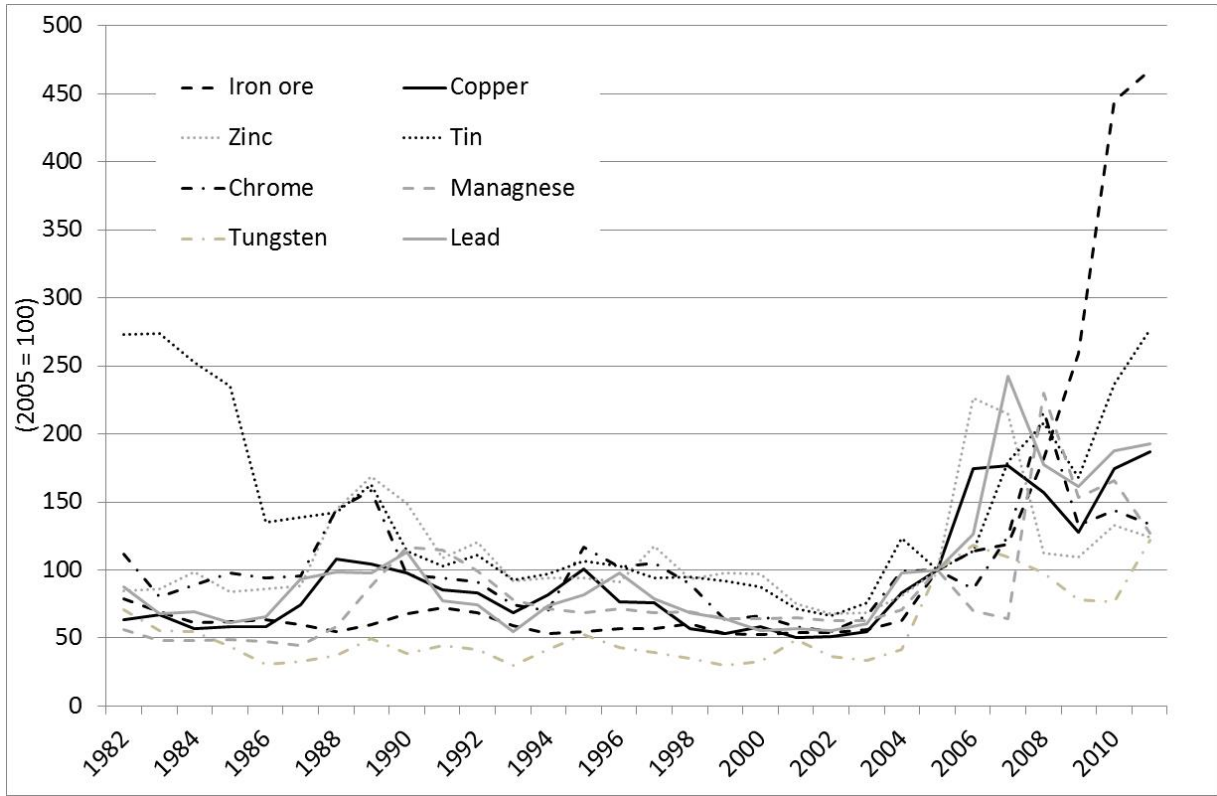


Figure 1: Deflated prices, base metals

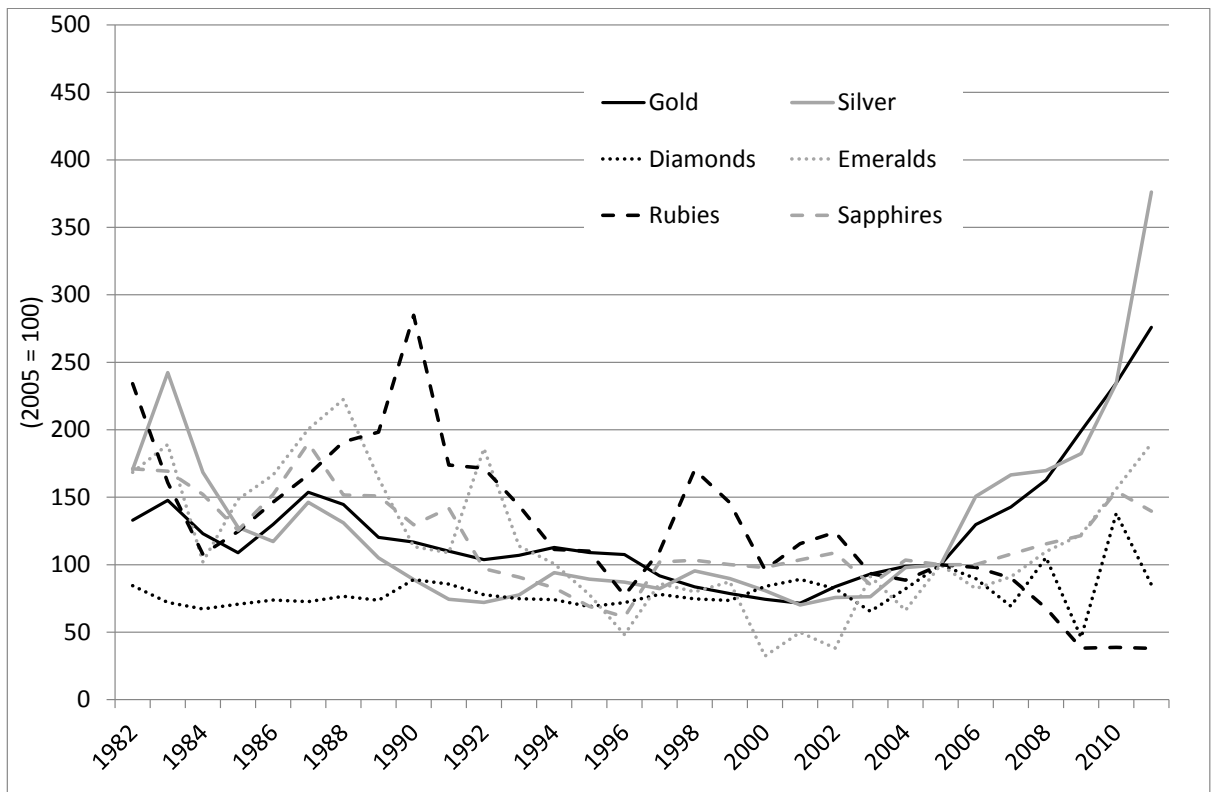


Figure 2: Deflated prices, precious metals and gemstones

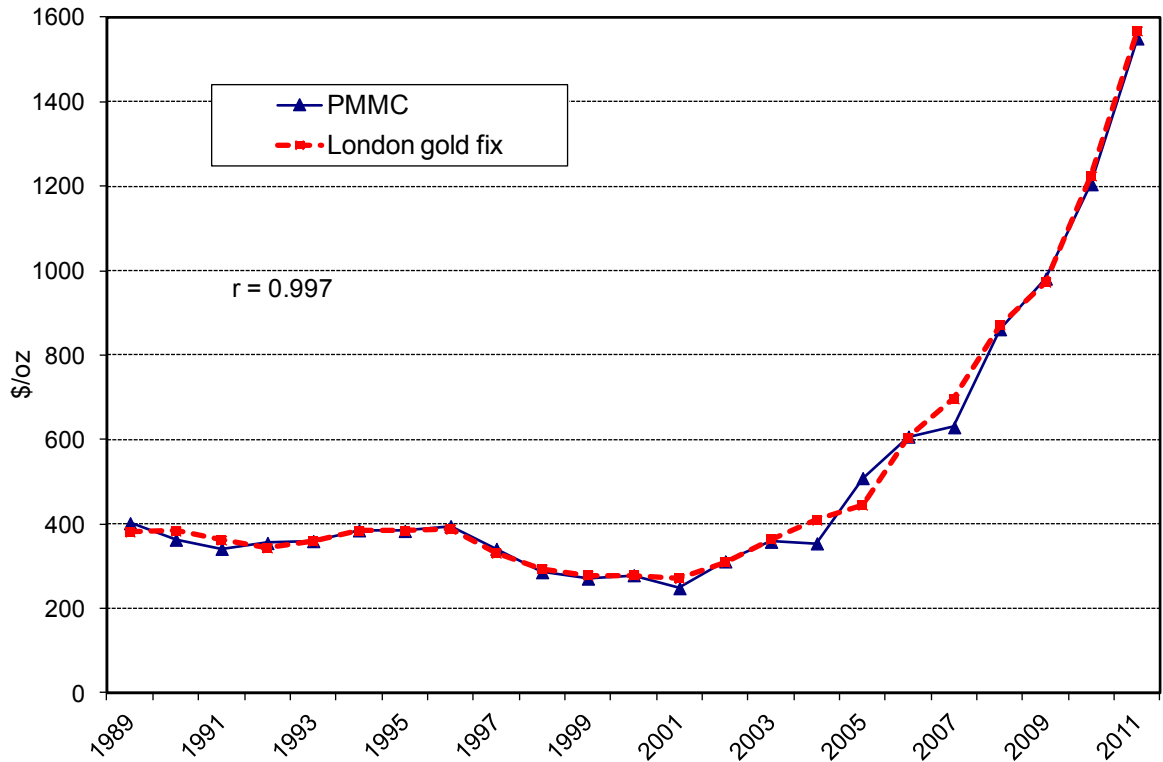


Figure 3: Ghanaian (PMMC) and World Gold Prices, 1989-2011

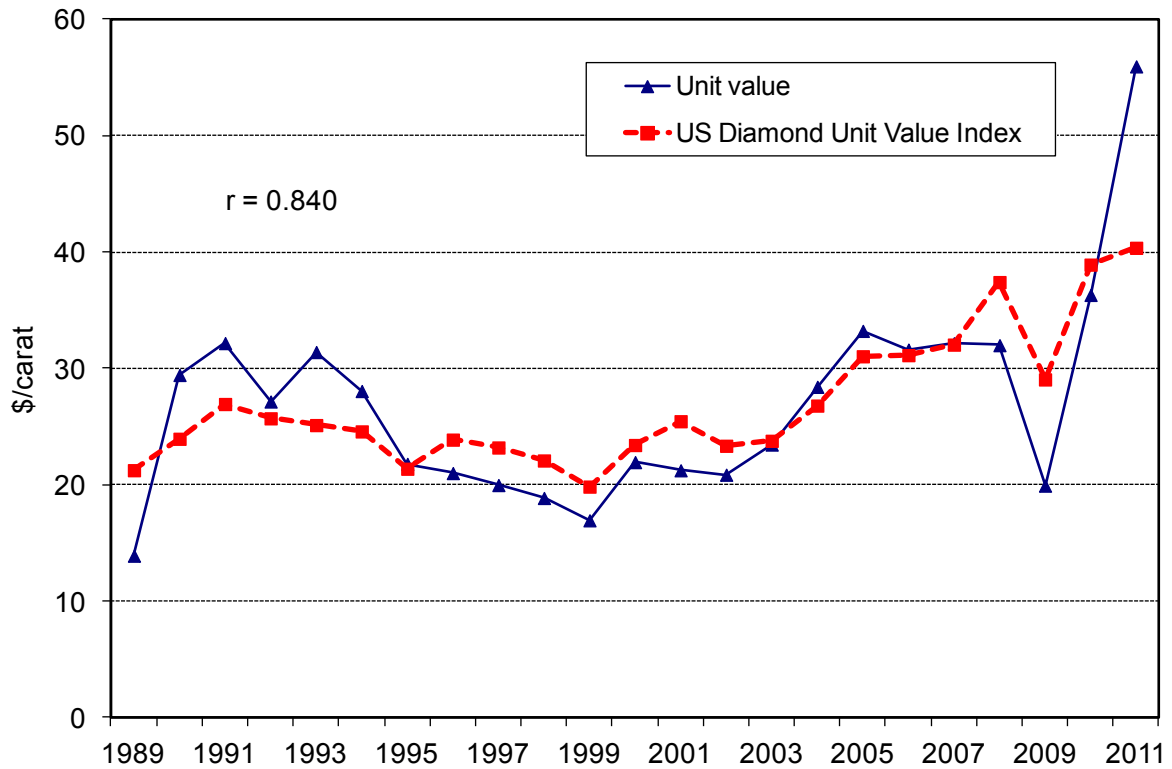


Figure 4: Ghanaian (PMMC) and US Diamond Prices, 1989-2011

	ASM share in total	Share in total ASM
Iron Ore	12%	42.8%
Gold	10%	17.6%
Copper	8%	11.2%
Zinc	11%	6.1%
Tin	15%	5.1%
Chrome*	50%	3.5%
Silver	10%	3.2%
Manganese	18%	3.2%
Tungsten	80%	2.4%
Lead	11%	2.4%
Others		2.5%

The first column gives the estimated share of ASM production in total primary production of the metal as reported by the U.S. Bureau of Mines. The second column gives the share, by 1983 value, of ASM production of the metal relative to the estimated total value of ASM metal production.

* as chromite.

Source: Carman (1985).

Chrome	171%	Gold	196%	Cocoa	88%
Copper	203%	Silver	225%	Coffee	79%
Lead	239%			Cotton	93%
Manganese	185%	Diamonds	116%	Groundnut oil	90%
Tin	205%	Emeralds	179%	Maize	85%
Tungsten	249%	Rubies	60%	Palm oil	89%
Zinc	155%	Sapphires	124%	Rice	96%
Iron ore	393%			Sorghum	84%
All base metals	231%	Precious metals	211%	All agriculturals	88%
Non-ferrous	207%	Gemstones	120%	Food products	89%

Data sources: copper, lead, tin and zinc, World Bureau of Metal Statistics, *World Metal Statistics*; chrome (unit value, as ferrochrome), manganese (unit value, as ferromanganese), tungsten (as ammonium paratungstate): U.S. Bureau of Mines, updated from *Metal Bulletin*; cocoa, cotton, gold, groundnut oil, maize, palm oil, rice, silver and sorghum – IMF, International Financial Statistics; coffee – International Coffee Organization (ICO Indicator Price); diamonds, emeralds, rubies and sapphires - U.S. Department of Commerce, <http://www.usatradeonline.gov>

Simple averages are reported throughout.

Cocoa, coffee and cotton are non-food agricultural commodities.

Table 3
Volatility of Annual Price Changes

	1983-2005	2006-11	Equality		1983-2005	2006-11	Equality		1983-2005	2006-11	Equality
Chrome	24.9%	42.7%	2.93**	Gold	10.7%	7.2%	2.21	Cocoa	19.6%	13.6%	2.08
Copper	20.1%	31.5%	2.45*	Silver	17.7%	22.0%		Coffee	28.2%	10.1%	7.71**
Lead	21.9%	34.0%	2.42*				1.55	Cotton	17.3%	21.3%	1.53
Manganese	17.7%	66.7%	14.21***	Diamonds	12.3%	73.0%		Groundnut oil	23.3%	32.2%	1.92
Tin	20.9%	28.2%	1.83	Emeralds	43.8%	18.3%	35.6***	Maze	15.6%	19.7%	1.60
Tungsten	30.9%	28.7%	1.16	Rubies	26.5%	28.6%	5.72**	Palm oil	28.8%	22.5%	1.64
Zinc	20.1%	48.9%	5.46	Sapphires	18.4%	12.9%	1.17	Rice	13.1%	29.4%	5.06***
Iron ore	14.1%	21.5%	2.33*				2.04	Sorghum	13.8%	21.2%	2.38*
All base metals	21.3%	37.5%	3.10**	Precious	14.2%	14.6%	1.06	All agriculturals	20.6%	21.4%	1.09
Non-ferrous	22.3%	29.8%	3.17**	Gemstones	25.3%	27.5%	3.54**	Food commodities	18.9%	25.0%	1.75

Volatilities are standard deviations of log nominal price changes. The final two rows are averages. The equality test is the standard *F* test for equality of two variances. Asterisks indicate significance at the 10% (*), 5% (**), and 1% (***) levels respectively.

Data sources: see Table 2

Table 4					
Average inter- and intra-group correlations, 1983-2011					
	Non-ferrous metals	Iron ore	Precious metals	Gemstones	Agricultural products
Non-ferrous metals	<i>0.351</i>				
Iron ore	0.268	-			
Precious metals	0.244	0.371	<i>0.775</i>		
Gemstones	0.167	0.284	0.111	<i>0.215</i>	
Agricultural products	0.177	0.111	0.284	0.020	<i>0.314</i>
Correlations are estimated for log price changes averaged across groups. The italicised diagonal entries are within group correlations. Data sources: see Table 2.					

Appendix 1 – industry characteristics

The appendix provides brief descriptions of each to the metals listed in Table 1 as important in the ASM sector. Similar information is provided for diamonds and coloured gemstones.

Chrome:

Chrome occurs as chromite which is iron chromium oxide and is the main source for the metal chromium. It often crops with magnesium. When melted at high temperature, chromite yields ferrochrome which is the form in which it is typically traded. The largest deposits are in southern Africa but India and Kazakhstan are also important producers. Although there are large ferrochrome mines on South Africa, a very substantial share of the market is satisfied by the small scale sector.

Copper: Copper mining predominantly takes place in large and medium sized mines. Some of the largest mines, such as Bingham Canyon in the USA and Chuquicamata in Chile, are among the largest mines in the world. The economies of scale which make the large mines highly profitable also make small scale mining relatively unprofitable. A consequence is that where small scale mining does exist, it often requires subsidization.

Despite this, there is significant small scale copper mining in South America. Enami, the Chilean governmental enterprise which promotes the small and medium-sized sector, provides a possible model for other countries. Enami remains reliant on heavy subsidies. The mines supported by Enami, many of which are medium rather than small-sized, are generally in remote and arid Andean areas where there is little alternative employment. Population moved to these areas to exploit the copper deposits, and, in the absence of support, would now be obliged to move away.

Enami supports its client operations by buying copper from them at a price held above production costs. This involves an element of subsidy at times of low prices. This type of floor price guarantee may be seen as the provision of a free put option. That being the case, there may be merit in making this explicit. Firstly, this would allow the Chilean government to value the cost of future support explicitly on an ex ante basis instead of waiting to see the ex post subsidy outcome. Secondly, the government could use financial markets to lock into

the ex ante cost by purchase of market options, or through the construction of synthetic positions using futures.

The Chilean government's continued support of Enami, which is doubtless also motivated by electoral considerations, may be seen as a closure policy. The strategy is to allow smaller mining companies to work out existing, largely depleted, deposits so that population declines gradually over time. It is arguable that the costs of this strategy are lower than alternative and more precipitate closure strategies. Whether or not this is the case will depend on the extent to which the strategy is successful in supporting existing mines without encouraging new investment. If within an explicit option scheme of the type outlined above, the government were to ask mining companies to cover a proportion of the option premium, this would reduce the extent to which Enami is obliged to support mines which would make severe losses in the absence of subsidies.

Gold: Gold mining takes place at an artisanal level, in small scale mines and in much larger mines often owned and operated by major mining companies. Extraction can either be alluvial, through open pit extraction or by underground mining. Although artisanal mining is generally alluvial, small scale mining can use any of these technologies.

The gold mining industry exhibits a low degree of concentration and there are no dominant players. Prices are determined competitively and, since the U.S. Federal Reserve Board ended its commitment to buy and sell gold at a fixed price in 1971, there has been no direct governmental intervention in the gold market. Despite this, the gold price has been among the least variable of all commodity prices – see below. This lack of variability is the consequence of the enormous stock of gold in the world, both that in the hands of the private sector, either as a store of wealth or in the form of jewellery (which may also be a store of wealth), or held by central banks as part of their reserve – see Lawrence (2003).

The World Gold Council reported total world official reserves of 28,338 tons at the end of 2012, little changed from the figure of 29,096 tons at the end of 2002. The U.S. Geological Survey reported 2012 world gold production at 2659 tons. Official gold reserves are therefore equivalent to over ten years annual production. To this should be added the impact of privately held stocks. Gold Fields Mineral Services has estimated the total stock of above ground gold at the end of 2001 as 145,200 tins (Lawrence, 2003), although this

estimate is necessarily impressionistic. Subtracting official reserves gives an estimate of the privately-held stock at that time as 113,400 tons.

There are multiple risks in artisanal and small scale gold mining – see, for example, Heemskerk (2003) – but these relate primarily to weather, yield and, depending on the ease or difficulty of releasing the gold, on pollution risks. Price risk does not appear high on this list, at least on the basis of the historical experience. This conclusion is reinforced by the low gold volatility figures reported in Table 2.

Iron ore: Iron is one of the most common elements in the earth's crust and, with coal, it is the single most important mineral by weight. It is found as iron oxide in either the hematite or magnetite ores, as iron hydroxide (goethite or limonite) and as iron carbonate (siderite). The predominant use is in the production of steel, accounting for around 90% of all iron ore.

The iron ore industry exhibits very substantial economies of scale since ore deposits can be both large and easily proved to be large. The industry is highly concentrated with three multinational mining companies dominating world production. Differently from non-ferrous metals, iron ore has a low value-to-weight ratio which implies that transport costs can be a large proportion of the price paid by steel makers in the consuming market. This allows small scale miners to compete in many markets to which transport costs are high, despite the higher mine production costs that they face.

Until very recently, iron ore prices were determined through the negotiation of annual supply contracts between the Australian and Brazilian miners and Japanese steelmakers. That system has not survived the replacement of Japan by China as the major consuming market. Most iron ore is now priced on a spot basis or against the Singapore futures market.

Lead and zinc: Lead and zinc tend to crop together – sphalerite which is zinc sulphide, with galena, which is lead sulphide. The two metals are therefore best considered jointly. Lead also crops as a copper byproduct. The major consumption use of zinc is galvanizing while most lead is destined for automotive and other batteries. These two uses are generally estimated as accounting for over 50% of production of each metal. These two uses have different cycles with the consequence that, typically, either one market or the other is tight while the other is closer to balance. This tendency is exacerbated because of the high

proportion of lead (around 50%) arising from recycling while relatively little zinc is recycled. The prices of the two metals therefore tend to move in opposite directions in the short term.

Lead and zinc mining does exhibit economies of scale but mines are seldom as large as the major copper mines. Artisanal and small scale production occurs throughout the world and contributes significantly to total world production.

Manganese:

Manganese, which is very abundant in the earth's surface, is mainly mined either as pyrolusite (manganese dioxide) and rhodochrosite (manganese carbonate). High quality pure manganese nodules are also found often in proximity to the ores. There are some large mines but small scale mines are also important. The most important producing areas are Brazil, China, India, west and southern Africa and Ukraine.

Silver: Silver crops both as silver ores, principally argentite (silver sulphide) and chlorargyrite (silver chloride) and as a byproduct in copper, gold and lead-zinc mines. There is no dominant producing area and mining is spread throughout the world. Although no detailed information is available, it appears likely that much ASM silver production also arises as byproducts.

Tin: Tin occurs in two forms – cassiterite (tin dioxide) and tantalite (a complex mineral containing both tin and tantalum). Cassiterite may either be extracted alluvially or by deep mining while tantalite is non-alluvial. The tantalum content of tantalite is generally of greater value than the tin content. Both minerals occur in greatest abundance in Asia – China (now the largest producer), Thailand, Malaysia and Indonesia. Alluvial extraction (dredging or panning) is dominant in Thailand, Malaysia and Indonesia and is also important in China. The other important producing area is Peru, Bolivia and the contiguous area of Brazil where both technologies are employed. Africa has only a small level of tin production – predominantly in Nigeria and the Central African Republic.

Tin is an exception in the metals industries in so far as economies of scale appear quite limited. There are few very large operations and relatively little involvement on the part of major mining companies. Further, the importance of small scale and artisanal mining has

tended to increase over the past decade, contrary to the trend in other metal industries. Much of the growth in artisanal mining has been in Indonesia in the wake of the 1999 rupiah devaluation which has translated moderate dollar tin prices into very high local prices. As a consequence the dominant national producer P.T. Timah has been unable to prevent large numbers of artisanal miners from illegally operating on its terrain.

Tin stabilization was effective until the early nineteen eighties. Following the collapse of the tin agreement, tin price volatility fell to a low level although it has risen sharply over the past decade.

Tungsten: Tungsten crops as wolframite (iron-manganese tungstate) and scheelite (calcium tungstate). Approaching 90% of world tungsten is produced in China, the majority in small scale mines. It is typically traded as tungsten concentrate (tungsten trioxide). Prices outside China are largely determined by Chinese export policy.

Diamonds: Diamonds crop either in narrow volcanic pipes, which can be reached only by capital intensive deep mines, or alluvially. Alluvial diamonds have been washed down from pipes and this washing process also results in beach deposits, as in the Skeleton Coast in Namibia, and offshore deposits. If they are spread over a wide area, alluvial deposits can be difficult to control and title difficult to enforce. The consequence is that illegal mining becomes widespread.

Diamonds have been implicated in financing civil wars. This was most clearly the case in Sierra Leone – see Keen (2005). Ross (2003) distinguishes between “lootable” and “non-lootable” resources – alluvial diamonds, coca and opium are lootable, while non-alluvial diamonds and offshore oil are non-lootable. He finds that and only the former explain conflict incidence. See also Ross (2006). Despite widespread discussion of the so-called “resource curse” – see Auty (1993) and Sachs and Warner (1999) – many countries have profited enormously from diamond production. Experience suggests that a strong regulatory framework is required at least in relation to alluvial diamonds.

Historically, diamond prices have exhibited low variability as the result of price stabilization undertaken by the Diamond Trading Corporation (DTC), an arm of De Beers (Kretschmer,

2003). Decisions taken under the aegis of European Union competition policy¹¹ have substantially reduced the monopoly power of the DTC and made price stabilization unviable resulting in a sharp increase in price volatility – see below.

Coloured gemstones: There is a large variety of coloured gemstones. The International Colored Gemstone Association lists 57 different types of gem. Some of these 57 gemstones occur only in a very limited range of locations. Indeed, many coloured gemstones are much rarer than diamonds, where the De Beers cartel used advertising to create a myth of scarcity in order to justify high prices to consumers.

Coloured gemstones are typically mined in relatively small scale operations and artisanal mining is also important. However, there is an absence of good data on the extent to which this is true. They sell in relatively thin markets. Changes in production in particular producing area can therefore have a large impact on availability in the relevant market. This is a recipe for price volatility. There is a lack of publicly-available historic price data for the majority of these gems, but the unit value data for three most important coloured gemstones – emeralds, rubies and sapphires – are discussed in sections 3 and 4. They show that price volatility can indeed be high.

Because gemstones are often highly concentrated in terms of geographical location, governments of producing countries have the potential to exert a degree of monopoly power. Competition among the different coloured gemstones probably limits the potential for raising prices. However, through the establishment and financing industry or trade associations, governments could do more to promote sales of coloured gems.

¹¹ General Court of Justice of the European Union, Case T-170/06 *Alrosa v. Commission*, 11 July 2007.

Appendix 2 – impacts of price volatility

There are three periods, 0, 1 and 2. Output prices are p_0 , p_1 and p_2 . The small scale miner makes an investment decision in period 0 which commits him for periods 1 and 2. The artisanal miner commits his time for period 1 in period 0 and for period 2 in period 1. For simplicity, I take the price p_0 to be his break-even price. He only commits time for period 2 if $p_1 \geq p_0$. Seen from period 0, his expected net income contribution is $E[p_2 - p_0 | p_1 \geq p_0]$.

The small scale miner has a cost advantage of $a > 0$ over the artisanal miner so his net income contribution is $p_t - p_0 + a$ in each period.

The artisanal miner produces one unit of output for each period he produces. The small scale miner produces $q > 1$ units of output. There is no production uncertainty.

The price follows a random walk so $p_t = p_{t-1} + \varepsilon_t$ ($t = 1, 2$) where $\varepsilon_t : N(0, \sigma^2)$. The small scale miner's expected net income contribution is therefore just $2qa$. Instead, the artisanal miner's contribution is

$$E[p_2 | p_1 \geq 0] = E[\varepsilon_1 + \varepsilon_2 | \varepsilon_1 \geq 0] = E[\varepsilon_1 | \varepsilon_1 \geq 0] = \frac{\sigma}{\sqrt{2\pi}}.$$

Both the small scale and the artisanal miner maximize the expected utility of consumption c . For the small scale miner, who I take as having no other source of income, consumption is $c_t = q(p_t - p_0 + a)$ ($t = 1, 2$). It follows that $E(c_t) = qa$ ($t = 1, 2$). Turning to uncertainty (as seen from period 0), $Var(c_1) = q^2 E[\varepsilon_1^2] = q^2 \sigma^2$ and $Var(c_2) = q^2 E[\varepsilon_1^2 + \varepsilon_2^2] = 2q^2 \sigma^2$. The miner maximizes expected utility $E[u(c_1) + \delta u(c_2)]$ where $\delta < 1$ is the discount factor.

We can evaluate the uncertainty cost to the miner by asking what is the maximum insurance premium that he would pay to eliminate the price uncertainty. The premium μ solves the equation

$$u(E[c_1] - \mu) + \delta u(E[c_2] - \mu) = E[u(c_1) + \delta u(c_2)]$$

The left hand side of this expression can be approximated as

$$u(E[c_1] - \mu) + \delta u(E[c_2] - \mu); (1 + \delta)[u(qa) - \mu u'(qa)]$$

where the prime indicates a derivative. Expanding the right hand side we get

$$\begin{aligned} E[u(c_1) + \delta u(c_2)]; (1 + \delta)u(qa) + \frac{1}{2}(1 + 2\delta)u''(qa)q^2\sigma^2 \\ = (1 + \delta)u(qa) - \frac{1}{2}(1 + 2\delta)\rho_s \frac{u'(qa)}{qa} q^2\sigma^2 \end{aligned}$$

where $\rho_s = -\frac{cu''(c)}{u'(c)} = -\frac{qau''(qa)}{u'(qa)}$, the miner's coefficient of relative risk aversion

evaluated at $c = qa$. It follows that the insurance premium is

$$\frac{\mu_s}{qa} = \frac{1 + 2\delta}{2(1 + \delta)} \rho_s \left(\frac{\sigma}{a}\right)^2 \quad (1)$$

The artisanal miner will have income from other activities, in particular from farming. I take this income y as constant and known. Since I have assumed that he just breaks even at the price p_0 , his consumption in period 1 is therefore $c_1 = y + (p_1 - p_0)$ with expected value $E(c_1) = y$ and variance $Var(c_1) = \sigma^2$. His consumption in period 2 is $c_2 = y + (p_2 - p_0) \cdot 1(p_1 \geq p_0)$ where $1(\cdot)$ is the function which takes the value unity if the argument is true and zero otherwise. His expected consumption is therefore

$$E[c_2] = y + E[p_2 - p_0 | p_1 \geq p_0] = y + E[\varepsilon_1 + \varepsilon_2 | \varepsilon_1 \geq 0] = y + E[\varepsilon_1 | \varepsilon_1 \geq 0] = y + \frac{\sigma}{\sqrt{2\pi}}$$

This has variance (again as seen from period 0)

$$\begin{aligned} Var(c_2) &= E[c_2^2] - E[c_2]^2 = Var(\varepsilon_1 + \varepsilon_2 | \varepsilon_1 \geq 0) - \left(\frac{\sigma}{\sqrt{2\pi}}\right)^2 \\ &= Var(\varepsilon_1 | \varepsilon_1 \geq 0) + Var(\varepsilon_2) \cdot \Pr(\varepsilon_1 \geq 0) - \frac{\sigma^2}{2\pi} = \left(1 - \frac{1}{2\pi}\right)\sigma^2; 0.84\sigma^2 \end{aligned}$$

The artisanal miner's expected utility is $E[u(c_1) + \delta u(c_2)]$ as with the small scale miner which we can approximate as

$$\begin{aligned}
& E[u(c_1) + \delta u(c_2)]; (1 + \delta)u(y) + \frac{\delta\sigma}{\sqrt{2\pi}}u'(y) + \frac{1}{2}\left(1 + \left(1 - \frac{1}{2\pi}\right)\delta\right)u''(y)\sigma^2 \\
& = (1 + \delta)u(y) + \frac{\delta\sigma}{\sqrt{2\pi}}u'(y) - \frac{1}{2}\left(1 + \left(1 - \frac{1}{2\pi}\right)\delta\right)\rho_a \frac{u'(y)}{y}\sigma^2
\end{aligned}$$

where $\rho_a = -\frac{cu''(c)}{u'(c)} = -\frac{yu''(y)}{u'(y)}$, the artisanal miner's coefficient of relative risk aversion

evaluated at $c = y$. To obtain the insurance premium, approximate

$$u(E[c_1] - \mu) + \delta u(E[c_2] - \mu); (1 + \delta)[u(y) - \mu u'(y)]$$

It follows that the artisanal miner will pay a maximum insurance premium

$$\frac{\mu_a}{y} = \frac{1}{2}\left(1 + \left(1 - \frac{1}{2\pi}\right)\delta\right)\rho_a\left(\frac{\sigma}{y}\right)^2 - \frac{\delta}{\sqrt{2\pi}}\frac{\sigma}{y} \quad (2)$$

Comparing expressions (1) and (2), we see that while the small scale miner is always made worse off by increased price volatility, the artisanal miner may be better or worse off depending whether the risk aversion or the option term in equation (2) is dominant. So long as we focus on artisan miners for whom mining income is a supplement to their agricultural income, it will be reasonable to take the ratio $\frac{\sigma}{y}$ as being small. Since the uncertainty term

in equation (2) is proportional to $\left(\frac{\sigma}{y}\right)^2$, the second (Oi or option) term will dominate. The

farmer-miner will benefit from price variability by devoting time and other resources to mining when the price is sufficiently high but remaining on his farm if prices do not justify mining.

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