# The Rise and Fall of an Industry:

Entry in U.S. Copper Mining, 1835–1986

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#### Abstract:

The principal forces that led to the rise and fall of the U.S. copper industry are explored: cost-lowering technical change, formation of expectations, consolidation of the industry, and depletion of investment opportunities. I find that the introduction of the steam shovel, which enabled open-pit mining, was the most important technological breakthrough. Revisions of expectations of success were statistically significant but economically less important. Contrary to the conventional wisdom, concentration of ownership encouraged entry. Finally, depletion was primarily responsible for the decline in entry in later years. However, the same forces that led to success also contributed to decline.

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# 1 Introduction

The introduction of new firms, technologies, and projects is key to the evolution of modern economies and improvement in standards of living. It is therefore not surprising that economists have devoted much attention to uncovering the unobserved forces that determine whether and when to invest in new activities. This paper explores the forces that shaped new investment in a particular industry, the U.S. copper industry, in a historical context. To do this, I exploit new data on U.S. copper mining between 1835-1986.

The research is motivated by a number of empirical regularities.<sup>2</sup> First, entry peaked at the turn of the 20th century and entry of major mines peaked only a few years later. Moreover, most of the major mines that are active today are very old. As Tilton and Landsberg (1999, p. 134) note, "Companies can maintain their comparative advantage only by ensuring that high quality deposits are discovered or otherwise acquired to replace those being depleted." This is not happening in the U.S. today. Secondly, in spite of the fact that U.S. industrial production grew exponentially, domestic copper production was flat for many years and has recently fallen. Finally, the ratio of U.S. to world copper production rose from less than 5% in the early 19th century to about 80% in the early 20th century but is now back down to about 5%. While it is true that the U.S. is still a major producer of copper, its relative position has declined steadily since its peak in 1920.

Copper is an exhaustible resource and the life cycles of such industries can be very different from those of manufacturing and service industries. In particular, with an exhaustible resource, any factor that leads to the rise of the industry, such as cheaper processing techniques or profitable discoveries, can also lead to its decline. Indeed, by stimulating investment, efficiencies can cause earlier exhaustion.

In assessing the number of copper mines entering each year, I focus on four factors that might have contributed to the rise and decline of the industry: cost-lowering technical change, formation of expectations, consolidation of the industry, and depletion of investment opportunites.

Technical change encourages entry when it transforms uneconomic deposits into economic reserves. During the period of the study, there were three major technological breakthroughs that revolutionized the history of copper mining by opening up new opportunities.<sup>3</sup> First and most important, in the early 20th century the invention of the steam shovel caused large low–grade open–pit or strip mines to become economically viable. Second and somewhat later, the discovery of froth flotation allowed sulfide ores to be processed much more cheaply.

 $<sup>^{2}</sup>$  These regularities are documented later in the paper.

 $<sup>^3</sup>$  For a discussion of major technological changes in the copper industry, see Wilburn, Goonan, and Bleiwas (2001).

These two developments transformed the copper industry from one in which smaller high– grade underground deposits were mined into one in which larger lower–grade but cheaper surface mines became predominant. Finally, improvements in leaching technology that were introduced in the second half of the 20th century allowed cheaper processing of the more abundant oxide ores and facilitated recovery of metal from mine waste dumps.

Expectational factors or beliefs can also stimulate investment. Revisions in beliefs can be due to genuine learning about the profitability of the region from the decisions of others,<sup>4</sup> or they can be overreactions.<sup>5</sup> Indeed, mining has been subject to expectational bubbles or rushes. I do not try to distinguish between rational learning and overreaction because both are characterized by a flurry of exploration and entry of small marginal mines following the opening of major highly profitable projects, and both therefore depend on the history of major discoveries in the region in immediately prior years.

Unlike the first two factors, the effect of consolidation and increased concentration is ambiguous. On the one hand, if its primary effect is to enhance monopoly power, it can cause entry to fall as output is restricted. On the other hand, if its primary effect is to enhance efficiency through consolidation of resources and achievement of economies of scale, it can stimulate entry. Ironically, increased efficiency can hasten exhaustion whereas increased monopoly rent can retard it.<sup>6</sup>

Depletion is clearly an important factor. However, there are many ways to define depletion. I use the word here to denote a reduction in profitable investment opportunities. This is a very simple notion. However, it captures the idea that, in this industry, good investment projects are rare and may be becoming increasingly rare. In that sense, depletion will eventually lead to fewer and smaller deposits being developed and thus to the industry's ultimate decline. Moreover, as exploration can be viewed as sampling without replacement, since once a mine has been discovered it cannot be discovered again, depletion should depend on cumulative discoveries. However, the relationship between entry and cumulative discoveries is apt to be nonlinear. Indeed, entry can initially increase with cumulative discoveries, as success causes expectations of further success, but will eventually decline, as success ultimately leads to exhaustion.

To anticipate, I find that all four factors were significant determinants of entry patterns, albeit with varying magnitudes. Surprisingly, however, although the traditional view is that

 $<sup>^{4}</sup>$  Learning in extractive industries has been modeled in very different contexts by, for example, Hendricks and Porter (1987) and Smith and Thompson (2009).

<sup>&</sup>lt;sup>5</sup> See, e.g., Shiller (2005) on overreaction.

 $<sup>^{6}</sup>$  As Stiglitz (1976) and many others have pointed out, the effect of monopoly power on exhaustion is ambiguous.

industry concentration leads to output restriction,<sup>7</sup> I find that concentration stimulated entry. This finding is consistent with more recent theories that hold that firm sizes and boundaries are determined by considerations of efficiency, not market power.<sup>8</sup>

A number of checks are performed to determine if the basic model is robust. First, domestic primary copper competes with secondary or recycled metal and shifts in comparative advantage with respect to that sector could account for the decline of the domestic primary industry. Second, domestic copper also competes with imports from abroad and shifts in comparative advantage with respect to the rest of the world could also be an important factor. Third, since the U.S. borders on Canada and Mexico and both countries are major producers of copper, the effect on expectations of major mine openings in adjacent mining districts of foreign countries is evaluated. Finally, the effects of disaggregation, using states as regions, are explored. This exercise is particularly important for the expectation and depletion variables. Indeed, it is unlikely that, for example, a major find in Michigan will stimulate exploration in Arizona.

Additional checks involve evaluating the effects of major wars, copper cartels, price controls, and economic depressions. In theory, conditional on price and industrial production, which are clearly influenced by such events, entry should not be affected. Finally, other factors are assessed more informally. In particular, I ask whether deteriorating productivity, costly environmental regulation, and lower ore grades could be responsible for the decline of the U.S. industry.

The empirical estimations are based on a theoretical model of investment in an uncertain environment. Much has been written on this subject and most often such problems are cast in a real–options framework.<sup>9</sup> Furthermore, many authors have focused on the role of aggregate risk in discouraging aggregate investment. However, as Dixit and Pindyck (1994) point out, real–options models are not intended to describe the level of investment but instead they identify thresholds at which investment should occur. The model developed here involves risk averse investors who must form expectations about the profitability of their projects. With this model, uncertainty also discourages investment but for different reasons.

In what follows, the history of the copper industry and the four factors are discussed, the theoretical and empirical models are developed, the data are described, results are presented, and conclusions are drawn.

<sup>&</sup>lt;sup>7</sup> See, e.g., Bain (1951)

<sup>&</sup>lt;sup>8</sup> See, e.g., the transactions costs models of Williamson (1979) and the property rights models of Grossman and Hart (1986). It is also consistent with the more traditional Chicago School view that efficiency leads to concentration, not vice versa (e.g., Demsetz 1973 and Peltzman 1977).

 $<sup>^9</sup>$  See Carruth, Dickerson, and Henley (2000) for a survey of this literature.

## 2 Copper Mining in the U.S.

Archaeological evidence suggests that Native Americans mined copper in Michigan from at least 3,000 B.C. until as late as the sixteenth century and traded it throughout the Mississippi Valley and the Southeast.<sup>10</sup> Because the copper occurred in native form, that is as pure metal, sophisticated processing techniques were not required. By the time that Europeans arrived in Michigan, however, not only was copper no longer mined but the location of the early mines had been forgotten. Moreover, since copper nuggets had been carried by glaciers to far distant places, the mines were difficult to rediscover.

The earliest successful colonial copper mine was developed in Simsbury, Connecticut in 1707, and other mines were subsequently opened in New Jersey, Pennsylvania, and Vermont. Although some of those mines were profitable, production was insufficient to put U.S. copper on the map.

It was more than a century later in the early 1840s when Michigan once again became a major producer of copper. In 1841, Douglass Houghton, Michigan's first state geologist, published his findings concerning copper deposits in the Keweenaw Peninsula. When summaries of his remarks appeared in major newspapers, the "Michigan copper fever"<sup>11</sup> the first American copper rush — began. The Cliff mine, which opened in 1845, was the first profitable Michigan mine and its success stimulated further investment. Although many subsequent investments were marginal or unsuccessful, by 1880 Michigan was producing 84% of U.S. copper and the U.S. was producing about 20% of world copper. Clearly, the U.S. had arrived.

Michigan's heyday lasted until about 1890 when Montana became the biggest copper producer. In particular, the Anaconda mine that opened in Butte in 1880 was a spectacular success, causing the Butte region to be called "the richest hill on earth." Although many smaller mines opened in the region of Butte, little by little they were consolidated until they became one gigantic mine. Montana took the lead in copper production because its ores were closer to the surface and cheaper to process. In particular, froth flotation was first introduced in Butte to concentrate its rich ores.

Montana's reign as the top producer was short lived. Indeed, by 1910 Arizona had caught up and by 1920 its production was triple that of Montana. The Southwest, which also includes Nevada, New Mexico, and Utah, is still the dominant copper region of the United States. Production in the Southwest, however, tends to be very different from mining the rich

<sup>&</sup>lt;sup>10</sup> Historians differ as to the dates during which Michigan copper was mined. Much of the information on the history of copper mining in the U.S. that is reported here comes from Hyde (1998). For a brief account of world copper history over the last 7000 years, see Radetzki (2009).

<sup>&</sup>lt;sup>11</sup> Hyde (1998) uses this terminology.

veins that occurred in other regions. The new mines were of low grade and had previously been uneconomical. However, in 1906 the mining engineer Daniel Jackling introduced a new method of mining copper —the use of steam shovels and railroads in an open-pit setting in Bingham, Utah. This new technology, which caused Bingham to be called "the richest hole on earth," paved the way for the exploitation of the large low-grade porphyry deposits that still dominate world production.<sup>12</sup> Many large mines entered in a short period and, in fact, more than half of the twelve largest copper mines in the U.S. in 2005 entered in the decade between 1903 and 1913.

In the 1920s, the U.S. copper industry was at its peak. Although U.S. production continued to grow for a long time after that period, its position in the world market began to decline. Figure 1 shows U.S. copper output as a proportion of world output. The solid line is actual production whereas the dashed line is a fitted quadratic. The figure shows that the rise of U.S. dominance was steeper than the fall. However, with the exception of a precipitous decline during the great depression, which affected the U.S. more strongly than the rest of the world, an inverted U is not a bad approximation. My focus here, however, is not on the relative position of the U.S. mining industry. Instead, I focus on investment in new U.S. mines.

# 3 The Four Factors

The rise and fall of the U.S. copper industry is probably due to a variety of factors, and I focus on some of them here. In particular, I examine factors that affect costs, expectations, market structure, and depletion.

### 3.1 Technical Change

The production of copper metal from ores consists of four stages: mining, concentrating, smelting, and refining, with the output of the first being ore and the last pure metal. However, if the ore is sufficiently rich, some of the stages can be skipped. Most copper ores are either oxides (compounds with oxygen) or sulfides (compounds with sulfur). However, most of the copper mined in Michigan was native ore or pure metal.

Probably the most important breakthrough in U.S. copper mining occurred in Bingham, Utah in 1906, when the steam shovel was introduced in the first modern open pit mine. By lowering the cutoff or lowest economical grade, this innovation increased reserves substantially and facilitated the development of mass mining. In particular, the steam shovel

<sup>&</sup>lt;sup>12</sup> For example, most of the copper mines in Chile, by far the largest producer today, are porphyries.

enabled the switch from selective mining, where rich veins were exploited, to mass mining, involving very low–grade ore bodies. As Radetzki (2009, p. 182) notes this "switch was akin to a move from handicraft methods to large–scale industrial processes."

The second most important development was the introduction of froth flotation in Butte, Montana in 1911. As Fuerstenau (2007, p. 3) claims "No metallurgical process developed in the 20th century compares with that of froth flotation and the profound effect it has had on the mineral industry." This process, which is used to concentrate sulfide ores, lowered the cost of processing the deposits in Montana and many parts of the Southwest. Unfortunately, due to legal battles, the introduction of froth flotation was not as smooth as that of the steam shovel. In particular, many patent infringement suits followed the installation of the first flotation operation, and that litigation inhibited widespread adoption.

The third breakthrough was the introduction of the solvent extraction electrowinning (SX-EW) technology for leaching oxide ores. SX-EW, which is an alternative to smelting, involves the use of sulfuric acid to liberate the copper minerals. The SX-EW technology, which was first used commercially in the U.S. in 1968 at the Bluebird plant in Arizona, has a number of advantages including lower capital costs, faster startup times, and the ability to process mining waste dumps (U.S. Congress, 1988). An economical process to leach sulfide ores, however, still awaits development, as does the ability to recover byproducts.

### **3.2** Investor Expectations

Although mining rushes are usually associated with gold and silver, copper has also experienced periods of intense exploration. For example, the Michigan copper fever occurred in the early 1840s. Moreover, on May 25, 2012, a New York Times headline proclaimed "A Mining Rush in the Upper Peninsula." That article notes that, after Rio Tinto started working on a \$469 million copper/nickel mine in northern Michigan, "Smaller exploration firms are joining the rush, searching for new ore deposits and studying known ones." The question remains, however, is this overreaction — a bubble — or is it an example of rational investment?

A successful mine can be extremely profitable. To illustrate, in 1879, the prospector George Warren bet his one ninth share of the Copper Queen mine in Arizona, claiming that he could outrun a man on horseback a distance of 100 yards. Unfortunately for him, he lost the race and his share of the mine. When he died a pauper in 1892, his earnings would have been \$20 million or about \$500 million in today's dollars (Carter, 2012). When the prize is very desirable and the outcome is very uncertain, it is not surprising that many investors are willing to enter the game. Unfortunately, an evaluation of whether the exploration and investment gamble had a positive or negative expected payoff requires data that is completely lacking. For the purpose of this paper, the two phenomena are observationally equivalent. Both are characterized by a frenzy of exploratory effort and the opening of unprofitable or marginal mines following what is thought to be a large success. Moreover, Hyde (1998, p. 37) notes that the lags between the day a mine opened and the day it was proven a success or failure were so long that there were many opportunities to make a fortune through speculation, regardless of the outcome.

### **3.3** Consolidation and Concentration

Consolidation is perhaps the most interesting factor, first because its effect is ambiguous and second because its history is so colorful.

Much has been written about the motives for and effects of concentration of ownership into a few hands. Many economists believe that consolidation is motivated by considerations of market power and monopoly rent.<sup>13</sup> In other words, the structure/conduct/performance tradition hypothesizes that the causality runs from concentration to profits.<sup>14</sup> Many others, however, believe that efficient firms expand and take over the market (e.g., Demsetz (1973) and Peltzman (1977)). In other words, the Chicago–School tradition hypothesizes that the causality is reversed. Moreover, other economists such as Williamson (1979) believe that firm size is determined by weighing the transaction costs of interacting inside firms versus in arm's length markets.

Although transaction cost models are usually used to explain vertical structures, they can also apply to horizontal integration. To illustrate, the costs of horizontal-market interactions in Butte, Montana in the late nineteenth century were extremely high due to a peculiar law that was passed in 1872.<sup>15</sup> That law, the law of the apex, held that the mining rights on a tract of land belonged to the owners of the highest surface outcrop or apex of a vein. Those owners had the right to mine the vein even when it extended beneath the tracts of others. This provision led to costly litigation and even to battles in the mine shafts.<sup>16</sup> Furthermore, it led to inefficient acquisition of tracts of land adjoining a potential mining site in order to preempt and avoid the loss of a claim. Finally, even when legal challenges were not supported by the courts, they could cause lengthly postponement of mine development. The end result was that Anaconda eventually came to own almost all of the properties in the Butte area, which enabled it to not only avoid costly litigation but also to achieve economies

<sup>&</sup>lt;sup>13</sup> See Bain (1951) for an early view.

<sup>&</sup>lt;sup>14</sup> For a summary of structure/conduct/performance studies, see Weiss (1974).

<sup>&</sup>lt;sup>15</sup> The mining law of 1872 also established the system of private property rights that persist today. See Clay and Wright (2012) for an analysis of how this affected the industry.

<sup>&</sup>lt;sup>16</sup> See Joralemon (1973, p. 91–98) for a colorful history of the litigation and battles.

of scale. Interestingly, the Arizona mining companies learned from the Montana experience and voluntarily agreed to use vertical sidelines — ownership of all ore underneath a claim — rather than the law of the apex and thus avoided costly litigation without consolidation (Hyde, 1998, p. 117).

It would be naive, however, to believe that all consolidation was motivated by efficiency considerations. For example, the then dominant producer, Calumet & Hecla, and other Michigan mining companies attempted to restrict output in the 1870s and were partially successful. However, by the 1880s they had lost control of the market due to the emergence of the Montana mines. They were therefore happy to sign contracts agreeing to sell all of their output to the French Secrétan Syndicate later in the decade.<sup>17</sup> Determining the net effect of market concentration on entry and output is therefore an empirical issue.

### 3.4 Depletion

The word depletion has been used to denote many phenomena including falling output, rising market and shadow prices, costs that increase with cumulative production, and exhaustion of the resource base.<sup>18</sup> I use the word here to denote a somewhat different phenomenon that I call investment depletion. Investment depletion occurs when when new investment opportunities become scarce. In the context of mining, it means failure to discover high quality deposits that can replace those that are being depleted. Since successful mines are very long lived and production from those mines typically increases over time, investment depletion is expected to occur many decades before more conventional deletion sets in. Moreover, it can occur at different times in different regions. Nevertheless, copper is an exhaustible resource and, even if the size of reserves is not fixed, it is surely finite. This means that conventional depletion will eventually occur and that the life cycle of a mining industry can be seen as a race between technical change that augments reserves and depletion that leads to exhaustion.

Reserves are defined as deposits that are economical at today's prices and technology, implying that either higher prices or new technological developments can cause formerly uneconomic deposits to become reserves. In contrast to improvements in technology, which augment reserves, higher prices can be signs of depletion. Moreover, Herfindahl (1959) claims that, since the U.S. copper industry was workably competitive throughout most of its

 $<sup>^{17}</sup>$  For more on copper cartels, see Herfindahl (1959).

<sup>&</sup>lt;sup>18</sup> Although the simplest Hotelling (1931) model of optimal extraction of an exhaustible resource predicts that price will rise and production will decline monotonically over time, there are many factors, such as exploration and technical change, that can cause prices to fall and production to rise initially. For an analysis of the former see Pindyck (1978) and of the latter see Slade (1982b). For a survey of the literature, see Slade and Thille (2009).

history, copper prices on average reflected long run costs, and higher costs would be signs of exhaustion. Figure 2, which contains a graph of real copper prices between 1835 and 1986 (the dashed line), shows that there is no sign of an upward trend in real price. While there is no sign that conventional depletion is occurring and that the copper industry as a whole is approaching exhaustion, the position of the U.S. relative to the world has deteriorated. Figure 1 illustrates this claim.

With respect to investment depletion, the fact that only one of the eight largest U.S. copper mines today, Sierrita, was developed in the last 50 years indicates that the U.S. is not replacing its giant mines. Furthermore, even Sierrita came on line over 40 years ago, and the others that were developed in the last 100 years, Tyrone and the Continental Pit, were brownfield. Finally, table 4–2 in Tilton and Landsberg (1999), which lists 28 'significant' U.S. copper mines that produced between 1975 and 1995, shows that two mines entered and seven exited during the two decades. However, both of the mines that entered, Tohono and Flambeau, were short lived and, since that time, a further five have exited.

Investment depletion should ultimately set in as cumulative discoveries proceed. In particular, as exploration is sampling without replacement, eventually there will be few deposits remaining to be discovered. Nevertheless, since success raises expectations of further success, initially discoveries could encourage investment. However, if the relationship eventually turns down, it can be a sign that new investment opportunities are drying up and depletion has come to dominate, at least in the region of interest.

## 4 The Investment Model

In this section, I specify a model of investment by risk–averse investors. Although the model that is estimated is an approximation to the entry profit function, in other words a reduced form equation is estimated, the theoretical model is used to identify the variables that should enter the empirical model. Readers who are uninterested in technical details can skip to section 5 without loss of continuity.

## 4.1 The Profit Function

Suppose that investors have negative exponential utility functions, u(y) = -exp(-ry), where y is income and r is the investor's coefficient of absolute risk aversion, and that income from an investment project is  $y = NPV - I = E[NPV] - I + \epsilon$ , where NPV is the net present value of the project, I is the (certain) investment cost, and E is the expectation operator. The project is risky and the random variable  $\epsilon$ , which is normally distributed with mean zero

and variance  $\sigma_{\epsilon}^2$ , denotes that risk. Under these assumptions, certainty equivalent income, CE(y), is E(y) - r/2Var(y), expected income minus the risk premium.<sup>19</sup> Note that at this point exploration cost, which is not modeled, is sunk.<sup>20</sup>

One can therefore express the risk–adjusted expected profit from an individual project,  $\pi$ , as the expected discounted cash flow minus the investment cost minus the risk premium, RP,<sup>21</sup>

$$\pi = E(NPV) - I - RP. \tag{1}$$

There are a number of exogenous forces that drive profits and create uncertainty. First, world price p, which is assumed to be mean reverting, evolves according to<sup>22</sup>

$$\frac{\Delta p_t}{p_t} = \gamma(\bar{p}_t - p_t) + u_{pt},\tag{2}$$

where  $\Delta$  denotes a first difference,  $\bar{p}$  is the mean to which p reverts,  $\gamma$  determines the rate at which p reverts to  $\bar{p}$ , and  $u_p$  is normally distributed with mean zero and variance  $\sigma_{pt}^2$ . The mean to which p reverts and the variance of percentage changes in p are allowed to vary over time, which is consistent with, for example, a model of mean reversion with stochastic trend such as the one developed in Pindyck (1999).<sup>23</sup>

Although opening a very large mine can affect world price, if size is uncertain when the investment is made, it seems reasonable to assume that price is exogenous to the investor. Nevertheless, this assumption is tested in what follows.

Second, industrial production IP, which drives demand, is assumed to evolve according to a geometric random walk with drift,

$$\frac{\Delta I P_t}{I P_t} = \alpha_t + u_{IPt},\tag{3}$$

where  $\alpha$  is the growth rate of industrial production and  $u_{IP}$  is normally distributed with mean zero and variance  $\sigma_{IPt}^2$ . The growth rate of aggregate economic activity is assumed to affect profits because mineral industries are subject to boom and bust cycles. Moreover, there

<sup>19</sup> Note that this expression is exact under the above assumptions and is a second-order approximation for an arbitrary utility function.

 $<sup>^{20}</sup>$  Doggett and Leveille (2010) find that, out of 100 copper mines opened in the last 30 years worldwide, although over 90% were profitable conditional on having been discovered — yielding at least an 8% rate of return — only 40% could carry the cost of exploration.

 $<sup>^{21}</sup>$  Note that the latter could but need not include the option value.

<sup>&</sup>lt;sup>22</sup> There is no consensus concerning whether commodity prices are mean reverting or nonstationary. See Slade and Thille (2009) for a summary of the evidence. A slightly more general process,  $\Delta p/p = \gamma_1 \bar{p} - \gamma_2 p + u_p$ , nests a geometric Brownian motion with drift when  $\gamma_2 = 0$  and the model in equation (2) when  $\gamma_1 = \gamma_2$ .

<sup>&</sup>lt;sup>23</sup> Equation (2) can also be interpreted as a model with stochastic convenience yield as in Schwartz (1997). Although Pindyck and Schwartz specify models of the stochastic trend and convenience yield, respectively, I simply assume that the mean changes slowly.

is substantial evidence that those cycles are long, perhaps several decades (see, e.g., Slade (1982a) and Jacks (2013)). Investors would therefore like to enter the market when demand is growing, not falling.<sup>24</sup> In addition, costs (e.g., wages) can be affected by aggregate growth. With both cases, the growth rate of industrial production shifts the expected net present value of projects conditional on price.

Third, unit costs,  $c_t = c(T_t) + u_{ct}$ , where T is a vector of technology variables, change over time as technology improves. Let the variance of costs conditional on technology be  $\sigma_c^2$ .

Finally, conditional on observed price, demand, and cost factors, the investment decision is influenced by investors' expectations concerning the region, which can be rational or can be driven by bubbles or mining 'rushes.' I assume that expectations are formed based on the number of recent discoveries of major or highly profitable mines in the region,  $MM_t$ , and that this variable shifts  $E(NPV_t)$ .

Let  $\pi_t$  be the risk adjusted expected lifetime profit for a mine that is opened in period t, which depends on price as well as demand, cost, and expectational factors. Profit is thus a function of the following variables and parameters:  $p, \bar{p}, \gamma, \sigma_p, IP, \alpha, \sigma_{IP}, \sigma_c$ , a vector of technology variables, and the number of major mines that have been found recently. Finally, the 'parameters'  $\bar{p}, \sigma_p, \alpha$ , and  $\sigma_{IP}$  are assumed to vary over time. Let  $x_t$  be the vector of variables that affect  $\pi_t$ , and let  $\pi_{it} = h(x_t) + v_{it}$ , where  $v_{it}$  represents variables for mine i that are observed by decision makers but not by the econometrician.

### 4.2 Entry

Conditional on discovery, an agent will invest in mine i if

$$\pi_{it} = h(x_t) + v_{it} \ge 0. \tag{4}$$

However, profits are not observed, and  $\pi_{it}$  is a latent variable. Instead of profitability, we observe the year of entry of each mine. Let  $I_{it}$  be an indicator function that equals 1 if mine i entered in year t.

Investment depletion is expected to be influenced by cumulative discoveries. However, the relationship is apt to be nonlinear since cumulative discoveries, CD, play two roles. Early on they trigger investment and lead to further discoveries. However, investment depletes the resource base and can lead to a decline in future discoveries. I assume that CD determines the investor's subjective probability probability of discovery. If  $\phi_t = \phi(CD_t)$  is that probability, then the probability of entry is  $\phi_t PROB[\pi_{it} \geq 0]$ . We therefore have

$$PROB[I_{it} = 1|x_t, CD_t] = \phi_t PROB[h(x_t) \ge -v_{it}] = \phi_t F(h(x_t)), \tag{5}$$

 $<sup>^{24}</sup>$  Since there are fixed costs in mining, investors care about demand conditions independently of their effect on price.

where F is the cdf of v. It should be clear that an increase in any variable such as price that makes a project more profitable raises the probability of entry. Moreover, increases in risk discourage investment, since risk averse investors will require higher expected returns.

Now suppose that in every year a fixed number of agents,  $\eta$ , explore and each of those agents discovers a deposit with probability  $\phi_t$ .<sup>25</sup> Exploration/investment is an independent (across investors) draw from [0,1] that determines whether exploration yields a hit or miss followed by an independent draw from the distribution of v if a hit occurs.

Let  $N_t$  be the number of mines that entered in period t. For each integer n,  $PROB[N_t = n|x_t, CD_t]$  can be obtained as the probability of n successes in  $\eta$  independent trials. Let  $E[N_t|x_t, CD_t]$  be the mean of that distribution. Clearly, the variables  $x_t$  will affect the expected number of mines entering in period t in the same way as they affect the probability of entry of a single mine. Finally, we can express  $N_t$  as

$$N_t = E(N_t | x_t, CD_t) + \nu_t = H(x_t, CD_t) + \nu_t,$$
(6)

where  $\nu$  appears because realized and expected entries differ. In other words,  $\nu$  is a forecasting error, which is independent of x and CD by construction. Equation (6) will be estimated rather than (5) because (6) captures the level of investment rather that just the timing.

## 5 The Data

#### 5.1 The Variables

The data begin in 1835 or earliest available year and end in 1986. 1986 was chosen because the U.S. producer price of copper, which is assumed to be the price that triggers investment, ceased to be published at that time. The U.S. producer price was chosen because it was the most relevant price for investors during most of the period.<sup>26</sup>

The following industry and economy-wide variables were collected: the U.S. producer price of copper (PRICE), U.S. industrial production (INDP), U.S. and world primary copper production (QPUS and QWORLD, respectively), U.S. secondary production (QSUS), U.S. imports (IMP) and consumption (CONS), employment in the U.S. copper industry (EMP), four and eight firm concentration ratios for U.S. copper (CR4 and CR8), the yield of U.S. copper ores mined (YIELD),<sup>27</sup> and the U.S. wholesale price index (WPI, 1967=1). The

<sup>&</sup>lt;sup>25</sup> The number of investors can differ by year as long as that number is determined by  $x_t$ .

<sup>&</sup>lt;sup>26</sup> The London Metal Exchange price also existed during all but the earliest years in the period and is now the relevant price worldwide. The two prices behaved very differently. In particular, the producer price was more stable (see Slade (1982b) for a graph, and Slade (1991) for an analysis, of the two prices.)

<sup>&</sup>lt;sup>27</sup> Yield is metal produced divided by ore mined. It is closely related to grade. However, yield is less than grade, since metal recovery is never complete.

appendix contains a more detailed description of the variables, the sources from which they were obtained, and the years for which they are available. PRICE was deflated by the WPI to form a real price (RPRICE).

The following industry variables were constructed from the raw data: LRPRICE, longrun price, a ten-year moving average of past real prices; SD%CHPRICE, the standard deviation of percentage changes in real price using the previous 10 years; %CHINDP, the percentage change in industrial production, and SD%CHINDP, the standard deviation of percentage changes in industrial production also using the past ten years. These variables represent  $\bar{p}$  and  $\sigma_p$  in equation (2) and  $\alpha$  and  $\sigma_{IP}$  in equation (3), respectively. Finally, CD or cumulative discoveries is constructed from entry in all past years.

I follow Harchaoui and Lasserre (2001), who average using a fixed period prior to opening to determine the parameters of the exogenous driving forces. If the parameters of the model,  $\bar{p}$ ,  $\sigma_p$ , and  $\sigma_{IP}$ , change slowly and in an unpredictable fashion, it seems reasonable that firms will form expectations based on local sample means of those parameters. The choice of 10 years is somewhat arbitrary. However, I experimented with longer and shorter periods.

There are a number of advantages to using a long-run price,  $\bar{p}$ . First, people in the industry claim that investment decisions are made on the basis of a long-run price. Second, it is no longer crucial to determine the precise year when an irreversible decision was made, as it would be if current price were used.<sup>28</sup> Finally, a long-run price is less apt to be endogenous.

Individual mine data were obtained from a search involving history books, company reports, newspaper articles, the internet, and the files of copper commodity specialists at the U.S. Geological Survey (USGS). Mines were selected only if copper was listed as the principal commodity. In particular, it is assumed that entry responds to the price of the principal commodity rather than to the prices of byproducts. Unfortunately, this is not always the case. For example, when the price of gold is very high, mines in which gold is a byproduct might enter. Nevertheless, that is the exception, not the rule.

The data include a total of 438 copper mines; 350 or 80% have entry dates, and of those with entry dates, 337 or 96% entered after 1835. The data contain all of the substantial mines and account for a very large fraction of U.S. production during the entire period. Montana is least well covered. Unfortunately, when the consolidation that is described earlier occurred, much of the history of the smaller mines near Butte was lost. The numbers of mines entering

<sup>&</sup>lt;sup>28</sup> Since averages use past data, the implicit assumption is that it takes one year to build the facility. However, if for example, if it takes three years, the long run price captures the history of prices prior to the decision as well as forecasts of future prices. If forecasts are based on price history and expectations are rational, realized and forecast prices will differ by an iid random variable. Moreover, the forecast error should not be correlated with any of the explanatory variables, which are also lagged.

each year, ENTRY, was constructed from this data.

Some mines are classified as major or highly profitable. This classification uses the information sources that are described above. In addition, the set of major mines was verified through consultation with USGS copper specialists. There are 35 major mines. The major mine variable (MM) was constructed as the number of major mines that entered in the previous five years.

## 5.2 Preliminary Data Analysis

Figure 3 shows the number of mines entering (ENTRY) each year as well as fitted linear and quadratic trends. The graph indicates that entry peaked around the turn of the 20th century. Figure 4, which contains the number of major mines entering each year (MAJOR), shows that entry of major mines peaked around 1910, only slightly later than entry in general.

Figure 2, which contains real copper price (RPRICE) between 1835 and 1986, shows a slight downward trend overall that is much more pronounced in the early years. More recently, however, after a sustained low period, prices began to rise quickly in 2004, fell at the end of 2008, but rose sharply again after that. I assume that there is no long–run trend in copper price but that the mean to which price reverts shifts over time, as in equation (2). Figure 2 also contains a plot of the long–run (LRPRICE), which is much smoother than and lags behind RPRICE.

The behavior of industrial production, in contrast, is very different. Figure 5, which charts U.S. industrial production (INDP) and a fitted exponential trend, shows that exponential growth, as is implicit in equation (3), is a good approximation.

Table 1 contains names, descriptions, and summary statistics for the principal variables. The table, like the figures, shows that there is substantial time–series variation in all of the covariates.

## 6 The Econometric Model

### 6.1 Estimation

The dependent variable, ENTRY, is discrete and nonnegative. Moreover, histograms reveal that ENTRY is strongly skewed to the right. Techniques for analyzing count data, which avoid negative predicted values, are therefore appropriate. The simplest count data model is based on the Poisson distribution. However, that distribution restricts the mean and the variance to be equal. When this restriction is not met, one can either scale the standard errors to compensate for over or under dispersion or select a more flexible distribution. In particular, a negative binomial is often more appropriate in cases of over dispersion. Standard tests of specification are used to select an appropriate distribution.

## 6.2 Identification

The explanatory variables are of two types: economy wide and industry wide. The economy wide variables, such as industrial production and the economic dummies for wars and depressions are clearly exogenous. Moreover, copper cartels were international in scope. Finally, the new technologies were applicable to more than one industry.<sup>29</sup>

Industry wide variables might or might not be exogenous. I have argued that, since mine size is not known when the investment decision is made, price is exogenous to the decision maker. Moreover, LRPRICE is a moving average of lagged prices that does not include current realizations. The past discovery variables, CD and MM, are assumed to be exogenous for similar reasons. In particular, like long–run price, the discovery variables do not include current realizations. To be safe, however, all of these assumptions are tested below.

This leaves the concentration ratios, and they are very apt to be endogenous. Indeed, the model is based on the latent-variable equation (4), and when concentration ratios are included in the x vector, that equation becomes one in which profits are determined by industry concentration. Although equations of this sort were frequently estimated in the past, they have fallen out of favor due to the difficulty of obtaining appropriate instruments.<sup>30</sup> Fortunately, historical data that spans a long period has an advantage. In particular, there were several major changes in the strictness of U.S. antitrust laws that occurred during the 150 year period, and these changes can be used to construct instruments. The instruments correspond to the passage of the Clayton act in 1914, the Celler–Kefauver act in 1950, and the Hart–Scott–Rodino act in 1976. These laws were attempts to strengthen and close loopholes in the Sherman act, which was passed in 1890.<sup>31</sup>

## 7 Results

In this section, a baseline model that includes the effect of resource depletion is estimated and variants of that model are assessed. All variants control for the possibility of depletion, since

 $<sup>^{29}</sup>$  The SX–EW technology is used only by the copper industry. However, that invention turns out not to be a significant determinant of entry.

 $<sup>^{30}</sup>$  See Slade (2004) for a discussion and critique of this literature.

<sup>&</sup>lt;sup>31</sup> Passage of the Sherman act is not used since the data on concentration start in 1911.

without that factor the results are not sensible. Other than that, however, no attempt is made to produce a final specification. In particular, presenting results from a preferred model with explanatory variables selected using a sequential hypothesis testing procedure would run into pre-test problems. Indeed, many papers have been written on the problems that are encountered when using data sets with many explanatory variables that are imperfect proxies for the underlying theoretical concepts and are often highly correlated with one another.<sup>32</sup> Moreover, those problems are exacerbated by the fact that, in many applications, the sample size is insufficient to allow one to draw conclusions on the importance of all potential regressors. As a result, that literature is highly critical of attempts to choose one 'preferred' model. In light of those arguments, I present results from a variety of models, both econometric and descriptive. The models, which are neither mutually exclusive nor definitive, are alternative explanations for the rise and fall of the copper industry.

## 7.1 The Baseline Model with Depletion

Table 2 contains negative binomial estimates of the entry equation.<sup>33</sup> All specifications include the long run price. The first equation, which also contains industrial production, is a straw man. With most intermediate industries, one expects high prices and high derived demand, as represented by industrial activity, to encourage entry. However, we find here that the estimated price effect is positive but insignificant whereas the effect of industrial production is significantly negative. This perverse result occurs because industrial production increased exponentially throughout the period whereas entry declined in later years. Note that, with a short time span, this effect would probably not be observed since year-to-year changes would dominate long-run trends.

For the second specification, industrial production is replaced by the growth of that variable. This specification fares somewhat better. In particular the coefficient of price is now significant, a finding that persists in most subsequent specifications. Nevertheless, although the sign of %CHINDP is positive, its coefficient is not significant at 5%.

The perverse findings for industrial production are due to failure to control for possible depletion, which is introduced in specification 3. In particular, cumulative discoveries, CD, and the square of that variable are included to allow for a nonlinear relationship with entry. The estimated relationship exhibits the predicted inverse U shape, with entry initially encouraged by discoveries as success breeds success but eventually discouraged as more and

<sup>&</sup>lt;sup>32</sup> See, e.g., Sala–i–Martin, Doppelhofer, and Miller (2004) and Tole and Koop (2011).

 $<sup>^{33}</sup>$  Heterosked asticity–consistent or robust standard errors are used. Durbin Watson tests showed no evidence of serial correlation.

more deposits are found. With this specification, the coefficient of %CHINDP becomes significant, a finding that also persists in most subsequent specifications.

The fourth equation includes the risk variables SD%CHPRICE and SD%CHINDP, which determine the risk premium RP in equation (1).<sup>34</sup> As predicted, increased risk discourages entry since, faced with more risky projects, risk–averse investors will require higher expected returns. Moreover, the effect of price uncertainty is stronger than that of demand uncertainty, which is not surprising since price variability is the primary risk. Indeed, in a competitive model with no frictions, capacity constraints, or fixed costs, conditional on price industrial production would be irrelevant. The fact that this is not the case here is evidence that adjustments are not costless.

Finally, just to be safe, an instrumental variable specification was estimated. The results can be found in table 3, which contains both OLS (column 1) and IV (column 2) estimates of the baseline equation. For the IV estimation, the prices of other commodities are used as instruments for copper price (see the data appendix), the hypothesis being that there are common shocks to commodity markets that do not affect long run decisions. The p–values at the bottom of the table indicate that there is no evidence of endogeneity, the instruments are not weak, and the over identifying restrictions are not rejected. Failure to reject the overidentifying restrictions has other implications. In particular, the null hypothesis is that the exogenous regressors and the instruments are uncorrelated with the errors, and CD is one of the regressors. Failure to reject the null is therefore evidence in favor of the exogeneity of CD.

Equation (4) in table (2) is the baseline model — the minimum model that makes economic sense. In what follows, extensions of this model are introduced.

## 7.2 Further Analysis of Depletion

In this subsection, I dig further into the notion of investment depletion. The initial results indicate that investment in new mines is initially encouraged by the discovery of more mines but eventually discouraged as depletion sets in. However, it is possible that these findings are spurious and are due to failure to consider common causal factors. Two hypotheses are investigated, and both involve the role of competing sectors. The first hypothesis is that, as more and more primary copper was produced, the supply of secondary or recycled copper increased, and production from scrap replaced primary production because it was cheaper.

 $<sup>^{34}</sup>$  One might wonder if total risk or just systematic risk is relevant for investors. I use total risk for two reasons, First, many early investors were small and did not have access to well developed capital markets. Second, Slade (2001) estimates a CAPM, where the asset is copper metal, and finds that one cannot reject the hypothesis that beta = 0. Nevertheless, I experiment with time varying betas below.

The second is that, as the U.S. producers began to invest more heavily in foreign mines, the supply of imported copper increased and imports replaced domestic production because they were cheaper.

Table 4 contains specifications that include the competing sectors. The first column, which investigates the role of secondary production, contains the variable QS/QP. That variable, which is constructed as a 10-year moving average of U.S. secondary divided by U.S. primary production, is a proxy for the long-run importance of the secondary sector. Column (1) shows that the coefficient of QS/QP is not significant at conventional levels, implying that competition from this source cannot explain the decline in entry.<sup>35</sup> Moreover, introducing the secondary sector does not alter the significance of the depletion effect in the primary sector.

The next two columns, which investigate the role of the foreign sector, contain the variable IMP/CONS. That variable, which is constructed as a 10–year moving average of imports divided by domestic consumption, is a proxy for the long–run importance of the foreign sector. Column (2) shows that, although the coefficient of IMP/CONS is significant, its sign is positive. Indeed, increased imports appear to encourage entry. However, if a decline in entry encourages imports, there is a reverse causality problem. For this reason, column (3) contains an equation that was estimated by two–stage least squares using lagged levels and growth rates of world copper production as instruments for IMP/CONS (see the data appendix). That specification shows that, once the endogeneiy of IMP/CONS is accounted for, the significance of its coefficient disappears. Moreover, the p–values at the bottom of the table indicate that the instruments are not weak and the over identifying restrictions are not rejected. Finally, as with the secondary sector, with both import specifications, introducing the foreign sector does not remove the depletion effect in the domestic sector.

As a final check, note that the variable CD was constructed from lagged endogenous variables and, if errors are serially correlated, lagged endogenous variables are not predetermined. However, the p-value in column (2) shows that there is no evidence of serial correlation.

## 7.3 Technical Change

The first extension of the baseline model introduces technical change. For this extension, dummy variables were created that equal zero prior to the year of the adoption of each new technology and one thereafter. The underlying assumption is that, once a technology

 $<sup>^{35}</sup>$  Although in theory this variable might be endogenous, its lack of significance implies that its exclusion does not cause a bias.

has been introduced, it is available to new entrants. The following dummy variables were created: DOPEN for open-pit mining (the introduction of the steam shovel), DFROTH for froth flotation, and DSXEW for solvent extraction electrowinning.

Table 5 shows estimates when each technological variable is introduced individually as well as when all are included. One can see that when each variable stands alone, the coefficients of DOPEN and DSXEW (but not DFROTH) are significant. However, contrary to expectation, the coefficient of DSXEW is negative. When all three technology variables are included, in contrast, the coefficient of DSXEW is no longer significant.

It appears that the introduction of the steam shovel and open-pit mining was the most important technological innovation for the copper industry. This change in the way that copper was mined enabled an entire new set of deposits to be exploited, and those deposits - the porphyries — have come to dominate the industry today.

It is less obvious why the other two technologies were not significant determinants of entry. However, with hindsight, explanations can be found. With respect to froth flotation, the legal battles over patent infringement that ensued meant that, contrary to assumption, the new technology was not freely available to all entrants and its introduction was more gradual. In particular, after the introduction of froth flotation, the fraction of U.S. copper production that came from sulfide ores increased significantly.

Although the introduction of the SX–EW technology was a major event, its primary effect was on extraction, not entry. Specifically, the amount of metal that could be extracted from existing waste dumps increased. In addition, oxide ores in older mines that had previously processed only sulfide ores became economical. Both of those effects increased production as well as the fraction of that production that came from oxide minerals. Indeed, the fraction of mine production that was processed by SX-EW rose from 1.2% in 1970 to 38% in 2000 (Bartos, 2002).

## 7.4 Expectations of Profitability

The second extension introduces investor expectations. I assume that when it becomes known that a mine is highly profitable — that is, when it is known to be a major mine expectations concerning the success of other investment projects are revised upwards. More precisely, I assume that investors have priors concerning the profitability of projects and, when the success of a major mine is determined, the mean of the prior distribution shifts to the right. The spread, however, is preserved. Moreover, since there is a lag between the opening of a mine and the determination of its profitability, the variable MM is constructed from lagged major openings. Furthermore, since the lag varies by project, a window of previous years is used. Table 6 shows several negative binomial specifications of the entry equation with different expectational variables.

#### 7.4.1 Baseline Model with Expectations

The first column in table 6 is the baseline specification with the number of major mines that entered in the previous five years added. It can be seen that expectations are indeed revised upwards based on major discoveries. However, the variable MM in those equations was constructed using a five-year window, which is somewhat arbitrary. To test if the results are sensitive to the specification of MM, two margins of the definition were varied. First, when different windows were used, it was found that as long as the window was not very different from five years, the positive and significant coefficient persisted. Second, experimentation with a smaller set of major mines — mines that were more clearly major— made little difference.

To investigate the possibility that MM might be endogenous, changes in property rights laws and agreements, which made ownership more secure and facilitated the outside investment that was needed to develop major projects, were used as instrument (see the data appendix). However, Durbin/Hausman/Wu tests failed to reject the exogeneity of MM. In particular, the p value for the exogeneity test was 0.89. In addition, the instruments are not weak (p=0.00) and the overidentifying restrictions are not violated (p = 0.21).

#### 7.4.2 Expectations Based on Mines in Adjacent Countries

The U.S. borders on Canada and Mexico and both countries produce substantial amounts of copper. It is therefore possible that major discoveries in adjacent mining regions of those countries affected entry in the U.S. In particular, large foreign discoveries might cause U.S. investors to revise their expectations upwards.

In Canada, copper is mined in Ontario, Quebec, and British Columbia. In Ontario, however, copper is almost entirely produced as a byproduct of other metals. B.C. and Quebec, in contrast, have mines in which copper is the primary activity. However, neither province borders on a major U.S. copper mining region.

Unlike Canada, Mexico has major copper mines that are very close to the Arizona border and the geology and mineralogy of those deposits is very similar to that of the Arizona mines. For this reason, major mines in northern Mexico (Sonora) were added to the data, which increases the number of major mines from 35 to 40. The second specification in table 6 includes an expectational variable (MMMEX) that was constructed using the augmented set of major mines. One can see that the coefficient of MMMEX is somewhat larger than the coefficient of MM in the second specification.

#### 7.4.3 Panel Estimations

Up to this point, the analysis has treated the U.S. as a single region. However, it is unlikely that, for example, the discovery of a major mine in Alaska would trigger exploration in California. For this reason, the data are now considered to be a panel where the regions are states. In particular, regional expectation and depletion variables are constructed. Unfortunately, the construction of those variables requires a large number of observations per state and only Michigan and Arizona have sufficient entry for that purpose. The panel therefore consists of just two regions.

Figure 6, which contains plots of entry in Michigan and Arizona, shows that the time pattern of entry was very different across regions. Both have 20–year periods of intense entry: 1845–1865 in Michigan and 1910–1920 in Arizona. However, although entry in Arizona looks very similar to entry in the U.S. as a whole, the pattern in Michigan looks more like an exponential decline.

The following regional variables were constructed: ENTRYREG is the number of mines entering the region, CDREG is regional cumulative discoveries, MMREG is the number of major mines that entered the region in the previous five years, MMMREG adds major mines in Northern Mexico to MMREG, and DAZ is a dummy variable for Arizona (region 2).

Columns (3) and (4) in table 6 contain the fixed effects panel specifications of the entry equation, where the specifications differ according to the construction of the regional expectational variable. The table shows that the coefficients of both expectational variables are significant at 1%. However, the coefficient and the log pseudolikelihood function are larger when major mines in Mexico are included (column 4). Furthermore, both coefficients are substantially larger and more significant that those for the U.S. as a whole (columns 1 and 2).

As a check, the coefficients of the regional expectation and depletion variables were allowed to vary by region. However, no regional differences were detected. This is particularly interesting for the depletion variables. Indeed, in spite of the fact that the shape (i.e., inverse U versus exponential decline) and timing of entry were very different across states, response to cumulative entry was not.

### 7.5 Consolidation and Concentration

The third extension involves assessing the possibility that market power inhibited entry, perhaps through overt or tacit collusion. Indeed, if firms wanted to limit production in order to increase price, limiting entry would be one method of accomplishing that goal. However, I argue in section 3.3 that it is also possible for consolidation to have been efficient, in which case it would have encouraged investment as costs were lowered. To see which of these possibilities predominates, one must turn to the data.

There are many possible measures of concentration, and one of the simplest is the n-firm concentration ratio, the output of the n largest firms divided by industry output. Although this measure ignores the tails of the size distribution, this can be an advantage when one has data only on the output of the largest firms. For this reason, I use four and eight firm concentration ratios (CR4 and CR8, respectively). Unfortunately, data constraints make it impossible to construct those ratios prior to 1911, which means that the period 1911–1986 was used for this analysis.

Table 7 contains OLS (1 and 2) and instrumental variable or IV (3 and 4) specifications that include concentration ratios. The instruments are dummy variables for changes in U.S. antitrust laws, all of which made consolidation more difficult (see the data appendix). The table shows that, regardless of specification, concentration encouraged entry. However, the coefficients of the concentration ratios nearly double when instruments are used, as expected. Indeed, since consolidation captures a negative externality, one expects a downward bias in the OLS estimates. Moreover, with the IV regressions, the coefficients of the other variables are more sensible and consistent with earlier results. Finally, the p-values indicate that the instruments are not weak and that the overidentifying restrictions are not rejected.

The finding that concentration encouraged entry is perhaps surprising. Moreover, the story that I told about efficient consolidation in Butte, Montana cannot be the only reason for the positive relationship, since the data pick up only the tail end of that consolidation. However, there was a comparable consolidation in Bingham, Utah somewhat later. That consolidation was not motivated by concerns about property rights, as had been the case in Montana. Instead, the problem was that open-pit mining of low-grade ores generated massive wastes and, as a result, control of loose material and landslides was a major safety concern, especially when one mine was located above another, as was the case for Highland Boy and Bingham. There, as elsewhere, consolidation of mines internalized the externality. In addition, consolidation made investment from outside the region more attractive. In particular, it was much easier for the large companies to attract outside investment funds. For example, after consolidation, the Guggenheims invested heavily in the Utah mines.

There is also the down side of the story. Starting in the 1960s, many of the large copper companies began to neglect their copper interests as they diversified into other areas. This strategy was usually unsuccessful, and the weakened financial position of the diversified firms facilitated their acquisition by others who also wanted to diversify, especially cash-rich oil companies. Indeed, between 1963 and 1984, nine U.S. copper companies were acquired by oil interests (Hyde, 1998, p. 194). Few of those diversification efforts proved successful, however, and most of the acquisitions were later spun off, sometimes mine by mine. At the same time, the U.S. Department of Justice blocked a number of mergers between copper producers.

There were, however, a few bright spots. For example, in 1988 SOHIO sold Kennecott to Rio Tinto Zinc, a multinational mining firm based in the U.K. Fortunately, that acquisition led to increased investment that allowed Bingham Canyon to return to its past glory as, if no longer the richest, at least one of the richest holes on earth.<sup>36</sup>

## 7.6 Sensitivity Analysis and Alternative Explanations

This subsection concludes the assessment of entry with an analysis of possible alternative factors that might have contributed to the rise and fall of the U.S. copper industry.

#### 7.6.1 Sensitivity Analysis

I experimented with a number of alternative specifications and report on two here. First, I varied the number of years over which the averages — the long-run price and the volatility measures — were taken. As the number of years is lengthened, the earlier data are less and less relevant, and as the period is shortened, the averages become less stable. When I tried five and 15 years, although the statistical precision of the volatility variables and the pseudo loglikelihood function were reduced, the qualitative nature of the conclusions was not altered.

Second, I calculated industry betas based on the CAPM, where beta is a measure of systematic risk that is associated with holding an asset. Unfortunately, due to data constraints this involved dropping approximately one third of the mines. Ideally, one would have data on firm or an aggregate of copper industry stock returns. However, using firm or industry stock returns would mean dropping an even larger fraction of the sample. Lacking those data, I considered an alternative measure of systematic risk, the risk that is associated with holding copper metal. A copper beta was then calculated as COV(RP,RM)/VAR(RM), where RP is the percentage change in real copper price and RM is the real return (capital gains plus dividends) on the S&P Composite Index. In order to capture entire business cycles, betas were calculated using data from the previous ten years. When those betas were included in the baseline regression, their coefficient was not significant. Moreover, the coefficient of the measure of total risk, SD%CHPRICE, did not loose its significance.

 $<sup>^{36}</sup>$  By that time, the Chuquica mata mine in Chile had surpassed Bingham.

#### 7.6.2 Global and National Economic Events

There were a number of international events that affected the copper industry as a whole. Furthermore, some events, such as the Great Depression, were felt more strongly in the U.S. than elsewhere. Nevertheless, conditional on price and industrial production, national and global economic conditions should have negligible impacts on entry.

To test this hypothesis, major wars, copper cartels, U.S. government price controls, and the Great Depression were examined. In particular, dummy variables were created that equal one during the periods of the events and zero elsewhere. The following wars were considered: the U.S. Civil War, World Wars I and II, the Korean War, and the War in Vietnam. Copper cartels are those that were identified by Herfindahl (1959) as well as CIPEC, which occurred somewhat later. Finally, price controls were in place during World War II and the War in Vietnam. The details of these constructions are found in the data appendix.

As expected, none of the coefficients of the major event variables was significant individually or jointly. For this reason, the estimations are not shown.<sup>37</sup> I simply note that the baseline model was qualitatively unaffected by these additions.

### 7.6.3 Descriptive Analysis

The relative decline of the U.S. copper industry is sometimes attributed to other factors, such as low productivity, declining ore grades, and costly environmental regulations, possibilities that are discussed here. The treatment, however, is descriptive, not quantitative.

Figure 7 contains a graph of labor productivity  $(QUS/(EMP\times50) - \text{the solid line})$  in the U.S. copper industry between 1911 and 1986. The trend is clearly upward. However, this strong growth is almost certainly due to increased mechanization and tells us little about total factor productivity (TFP). An examination of TFP is beyond the scope of this paper. However, Parry (1999) assesses TFP in the U.S. copper industry and finds that, after negative growth during the 1970s, TFP improved significantly in the 15 years that followed. It therefore seems unlikely that falling productivity led to the relative decline of the industry.

A fall in the quality of ores mined might also be a symptom of depletion, and grade is sometimes taken as a proxy for quality. Figure 7 also shows the average yield of copper ores mined in the U.S. between 1906 and 1986 (the dashed line).<sup>38</sup> With the exception of the Great Depression, when yield rose, yield clearly fell significantly over the period. However, due to improvements in technology, especially the advent of strip mining, low grade diffuse ore bodies became cheaper to mine than high grade veins. Indeed, as Clay and Wright

<sup>&</sup>lt;sup>37</sup> These results are available from the author upon request.

 $<sup>^{38}</sup>$  Yield is metal produced divided by ore mined.

(2012, p. 86) note, "From this perspective, reductions in average ore grades are a measure of technological progress rather than depletion." Nevertheless, the falling trend in yield, which continued well beyond the move to mass production, could have hastened the industry's decline. If this is true, falling yields are just another dimension of depletion.

Finally, although industrial wastes are regulated by the Resource Conservation and Recovery Act of 1976, wastes from hard rock mining and beneficiation (including flotation, solvent extraction, electrowinning, and leaching) are exempt from the Act (U.S. Environmental Protection Agency (2012)). In contrast, mineral processing wastes, including wastes from smelting and refining, have been regulated since the mid 1980's. In particular, processing facilities that generate non-exempt hazardous waste must obtain a permit, and the permitting process has delayed many recent projects. Nevertheless, only the last few years of my sample could have been affected by this requirement. Mining operations are also subject to the Clean Air Act of 1970 and the Clean Water Act of 1972, and those regulations, particularly the latter, impose substantial costs on mining companies. However, figures 1 and 2 show that copper's relative and absolute declines began long before 1970. Furthermore, when the baseline specification was estimated using only the years prior to 1970, the year when regulation of the industry began (column (5) in table 2), the results were very similar to those in column (4), which were obtained from the full sample. In summary, although environmental regulations have discouraged or delayed many recent investment projects,<sup>39</sup> those regulations cannot have precipitated the onset of the investment depletion, which occurred more than half a century earlier.

## 8 Magnitudes

Up to this point, only the directions of effects have been discussed. Magnitude are clearly important too. In this section, I assess the impact of the introduction of the steam shovel and open-pit mining, the discovery of a major mine, a change in asset ownership, and an increase in cumulative discoveries.

A coefficient in a negative binomial regression model shows the expected change in the logarithm of the dependent variable due to a unit increase in the explanatory variable. This means that, among other things, the point of evaluation is important. In each case, unless otherwise noted, I evaluate changes around the mean of the dependent variable.

<sup>&</sup>lt;sup>39</sup> In particular, in recent years three large copper mines have been tied up by environmental and land use regulations: Pebble in Alaska and Rosemont and Resolution in Arizona. Nevertheless, even if all three eventually enter, there will have been three major mines in the thirty years since 1986. This implies an average of one major mine every 10 years, which is much longer that the historic average of one every 4.3 years.

#### **Open Pit Mining**

After the introduction of the steam shovel, DOPEN changed from zero to one, causing an increase in ln(ENTRY) of 0.81. This change corresponds to an increase of 1.8 mines per year or, during the 80 year period after 1906, a total increase of 144 mines. This number might seem too large. However, one must recognize that this calculation assumes that all else is equal. In particular, this would have been the increase had no depletion occurred.

#### Revision of Expectations

The magnitude of the expectational effect will differ according to which specification of that equation is used. Two calculations are performed, one for the U.S. as a whole and the other for a regional specification. For the U.S., the coefficient of MMMEX in table 6, which is 0.127, is used. With this specification a major mine leads to the entry of 0.28 new mines per year. As this effect occurs over five years, the total increase is 1.4 new mines per major discovery. This number might seem too small. However, one must keep in mind that when the effect of cumulative discoveries is positive (i.e., in the earlier years) that variable also picks up increased expectations of profitability, implying that 1.4 is an underestimate. Furthermore, a flurry of exploratory effort might have been generated by a major discovery even if that effort resulted in only an average increase of 1.4 new mines.

For the regions, the coefficient of MMRMEX from the panel estimates (column 4 in table 6), which is 0.45, is used. With this specification, the total increase due to the discovery of a major mine is 2.3 new mines, which is larger than the first estimate. This finding confirms the importance of assessing the regions.

Although statistically significant and substantial, the effect of a single major discovery is not as economically important as the introduction of the steam shovel. Furthermore, the evidence of expectational bubbles is not particularly strong. However, in aggregate, discoveries of major mines are predicted to account for an increase of 63 mines in the U.S. as a whole (using the first estimate) and 35 mines in Arizona and Michigan (using the second). Nevertheless, unlike technical progress, it is unlikely that major discoveries substantially altered the number of mines that entered in the long–run. Instead, it is more likely that only the timing of entry was affected.

#### Changes in Industry Concentration

The 2SLS coefficient of CR4 is 0.092, which corresponds to an increase of 0.20 mines per year. However, CR4 is a percentage and changes of 1% are small. Instead, I evaluate the change from 40% to 60% that occurred in the 11 year period between 1920 and 1930. The associated change in entry is predicted to be 4.7 mines which, given that on average 2.2 mines enter each year, is substantial.

#### Changes in Cumulative Discoveries

In contrast to the other explanatory variables, whose effects depend only on the value of the dependent variable used in the calculation, the effect of cumulative discoveries (CD) also depends on the value of CD itself. Using the overall mean number of mines entering each year of 2.22 and the value of CD taken from 1900, I find that one additional mine would have increased the expected number of entries in 1990 by 0.09. By 1968, however, the 20 year average number of mines entering each year had fallen to 0.8, which is a substantial reduction in itself. Furthermore, one additional mine would have reduced that number by 0.02.

## 9 Final Remarks

The rise of the U.S. copper industry was influenced by many factors, and the advent of new technology, learning from the experiences of others, and consolidation of assets were some of the more relevant. On the down side, the decline was strongly affected by depletion of investment opportunities.

It is perhaps less obvious, however, that the factors that led to U.S. copper's success contributed to its decline. This is true because, unlike most goods and services, copper is an exhaustible resource. There are therefore limits to cumulative copper production. Factors such as technical change can transform uneconomic resources into profitable reserves. Unfortunately, however, nothing can augment the amount of copper in the earth's crust or change whether it occurs in significant concentrations, at least not in historic time. Factors that encourage investment can thus ultimately hasten depletion, and there are indications that this might be the case for the U.S. Not only has U.S. production declined relative to other countries but also the U.S. is not replacing its major mines, most of which were discovered nearly a century ago.

Although many industry experts see few signs that the world is running out of copper, some are more pessimistic. For example, Eric Finlayson, the then head of exploration for Rio Tinto, noted that, not only are U.S. but also Andean operations are starting to show signs of depletion. "The simple fact is that the industry as a whole is spending more on copper exploration than before and is delivering fewer resources." (Finlayson (2009)) Demand in contrast, led by China and other emerging economies, is rising. It is possible that this success — the growth in consumption — contains the seeds of a fall for the industry worldwide.

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# Data Appendix

The time–series industry and aggregate data were obtained from the sources listed below. Although an attempt was made to be complete, some data series do not span the entire period. In particular, some series were not available for the early years. I therefore list the years for which each variable is available.

#### **Industry Data Sources**

- ABMS: American Bureau of Metal Statistics, Non-Ferrous Metal Data, various years.
- CH: Stevens, H.J., 1902, *The Copper Handbook*, Vol. II: Mining Gazette Press.
- FRB: Federal Reserve Statistical Release Historical Data. Downloaded from the Internet.
- BLS: US Bureau of Labor Statistics Historic Data. Downloaded from the Internet.
- HS: Carter, S.B. et. al. Historical Statistics of the United States, Earliest Times to the Present, Millennial Edition, Cambridge University Press.
- MAN: Manthy, R.S., 1978, *Natural–Resource Commodities, A Century of Statistics*, Johns Hopkins University Press.
- MY: U.S. Bureau of Mines, *Minerals Yearbook*, various years, Early volumes are called *Mineral Resources of the United States* and were compiled by the U.S. Geological Survey.

• USGS: Porter, K.E. and Edelstein, D.L., *Copper Statistics*, U.S. Geological Survey. Downloaded from the Internet.

## Aggregate Data Series

- PRICE: Copper price in cents/lb. Sources: HS: 1835–1869, MAN: 1870–1973, MY: 1974–1986. In the early years, prices varied by region. I use the prices that HS reports. In particular, the price of sheathing is reported for the years 1835 to 1859 and of Lake copper for the years 1860 to 1869. For later years price is the U.S. Producer price.
- QPUS: U.S. copper production from mines, in 10<sup>3</sup> short tons. Source: HS: 1845–1869, MAN: 1870–1899, USGS: 1900–1986.
- QSUS: US Secondary production from old scrap, in 10<sup>3</sup> short tons. Source: USGS: 1900–1986. There was no large scale secondary production in the early years. For this reason, QS/QP is set to zero prior to 1900.
- QWORLD: World primary production of copper, smelters, in 10<sup>3</sup> short tons. Sources: CH: 1880–1899, USGS: 1900–1986.
- CONS: US consumption of refined copper in 10<sup>3</sup> short tons. These data pertain to copper used by the domestic industry (brass mills, wire rod mills, foundries, etc.). Sources: M: 1870–1973, MY: 1974–1986.
- IMP: US refined copper imports, in 10<sup>3</sup> short tons, Sources: M: 1870–1973, MY: 1974–1986. These data exclude semi-fabricated and manufactured products. Data for the years 1870–1979 are general imports, whereas for the years after 1979 they are imports for consumption. Imports were not significant in the early years. For this reason, IMP/CONS is set to zero prior to 1870.
- EMP: Employment in the U.S. copper industry, in 10<sup>3</sup> people. Source: MAN: 1911–1973, MY: 1974–1978, HS: 1979–1986.
- CR4 and CR8: Four and eight firm concentration ratios for U.S. copper mining in percent. These are constructed as the output of the four (eight) largest firms divided by industry output. Source: ABMS: 1911–1986. ABMS records copper production by company each year. Those statistics were used to compute the concentration ratios.

- YIELD: Yield is metal produced divided by ore mined. It is closely related to grade. However, yield is less than grade, since metal recovery is never complete. The average for copper ores mined in the U.S. is reported. Source: MY: 1906–1986.
- WPI: The U.S. wholesale price index, which later became the U.S. producer price index, 1967 = 1. Source: MAN: 1870–1973, BLS: 1974–1986. For the years prior to 1870, values were obtained by regressing WPI on the consumer price index (CPI from the BLS) and backcasting.
- INDP: An index of U.S. industrial production, 1905 = 100. Source: HS: 1835–1918, FRB: 1919–1986.

#### Mine Data

Individual mine data were obtained from a search involving history books, company reports, newspaper articles, the internet, and the files of copper commodity specialists at the U.S. Geological Survey (USGS). The date of entry is the year when production started. Unfortunately, this date is not consistently reported for some of the early mines. Whenever possible, the date reported in mindat.org is used here. A few mines are counted twice. This occurs when for example, an underground mine becomes a strip mine or when the type of ore that is mined changes dramatically. These cases require major new investments in mining or processing facilities.

Mines are classified as major when historic accounts portray them as highly profitable. Although this classification might seem arbitrary, when mines are mentioned by many authors, it seems plausible that those were the ones that might have triggered investment. Moreover, historians often note the economic influence that such mines exerted on the region where they were found.

#### International and National Event Data

*Wars:* US Civil War, 1861–1865; WWI, 1914-1918; WWII, 1939–1945; Korean War (US involvement), 1950–1953; War in Vietnam (US involvement), 1965–1973.

*Cartels:* Secretan, 1888–1890; Amalgamated Copper Restriction, 1899–1901; CEA, 1919–1922; CEI, 1926–1932; ICC, 1935–1939; and CIPEC, 1967–1988. Although cartels existed during these years, Herfindahl (1959) claims that the CEI was not effective in its first three years and that the ICC was never effective. Moreover, many experts feel that CIPEC's market power was negligible. A second cartel variable excludes those periods.

*Price Controls:* 1942–1946 during WWII and 1971–1973 during the War in Vietnam. There were also controls during WWI and the Korean War. However, the former are considered not to have been effective whereas the latter were accompanied by subsidies for investment in mining.

The Great Depression: 1929–1933.

#### Instruments

#### Commodity Prices:

PLEAD: The price of lead, in cents/lb. Source: HS: 1835–1986. PIRON: The price of pig iron, in cents/lb. Source: HS: 1835–1986.

The instruments were constructed by first deflating each price by the WPI to form a real price and then constructing a moving average using the 10 previous years.

#### World production:

A moving average of the rate of growth of QWORLD was created using the 10 previous years. In addition, once lagged values of QWORLD and its rate of growth were used as instruments.

#### Antitrust Laws

The Sherman Act, which was passed in 1890, was perhaps the most important antitrust legislation that was enacted in the U.S. However, since concentration ratios are available only after 1910, the passage of that act is not considered. Subsequent acts were basically amendments to the Sherman Act with the objective of strengthening it and closing loopholes. The following changes in antitrust law are considered: the Clayton Act, 1914; the Celler–Kefauver Act, 1950; and the Hart–Scott Rodino, Act, 1976.

#### The Property Rights Laws and Agreements

The following property rights laws and agreements are used to construct dummy variables. The passage of the Mining Law of 1872, the agreement on property rights (vertical sidelines) in Arizona in 1882, and the formation of Amalgamated Copper in 1910 to reduce litigation costs. The effect of the first on major investment is ambiguous whereas the effects of the second two are expected to be positive.

Variable	Description	Mean	Stan. Dev.	Minimum	Maximum
ENTRY	Indicator for entry	2.22	2.40	0	11
RPRICE	Real copper price	47.3	22.4	16.8	108.6
LRPRICE	Long run copper price	49.3	21.6	23.4	95.2
SD%CHPRICE	Stan. Dev., $\%$ change in PRICE	14.1	5.67	3.54	23.9
INDP	U.S. industrial production	364.7	518.0	2.03	1841
%CHINDP	% change in INDP	5.01	8.99	-23.1	27.4
SD%CHINDP	Stan. Dev., $\%$ change in INDP	8.38	3.70	1.51	18.4
CD	Cumulative discoveries	193.6	113. 3	0	337
MAJOR	Indicator for entry of major mine	0.230	0.592	0	4
MM	No. recent discoveries, major mines	1.15	1.66	0	7
QS/QP	US secondary/US primary production	19.9	23.2	0	115.6
IMP/CONS	US imports/US consumption	24.9	21.4	0	74.9

Table 1: Summary Statistics

	(1)	(2)	(3)	(4)	(5)
Variable				( )	Before 1970
LRPRICE	0.001	0.009	0.029	0.021	0.025
Long-run Price	(0.33)	(2.48)	(3.64)	(2.57)	(3.19)
SD%CHPRICE				-0.054	-0.043
Price Volatility				(-2.47)	(-2.12)
INDP	-0.0001				
Industrial Production	(-3.91)				
%CHINDP		0.016	0.019	0.021	0.022
Growth in INDP		(1.59)	(2.02)	(2.19)	(2.27)
SD%CHINDP				-0.040	-0.063
INDP Volatility				(-1.37)	(-2.14)
CD			0.024	0.033	0.030
$Cumulative \ Discoveries$			(5.45)	(5.73)	(5.37)
$\mathrm{CD}^2$			-0.00006	-0.00008	-0.00007
CD Squared			(-6.06)	(-6.14)	(-5.44)
CONSTANT	0.960	0.253	-2.578	-1.578	-1.726
	(3.56)	(1.09)	(-3.18)	(-1.77)	(-2.06)
log pseudolikelihood	-294	-299	-283	-278	-260
lpha	0.730	0.830	0.499	0.450	0.410
	(5.00)	(5.16)	(3.90)	(3.95)	(3.63)

Table 2: Negative Binomial Entry Equations with Depletion, Baseline Model

The dependent variable is the number of mines entering each year.

z scores are shown in parentheses.

Robust standard errors are used.

Columns (1)-(4) use observations from the entire sample, 1835 to 1986.

Column (5), which uses observations from 1835 to 1970, is discussed in subsection 7.6.3.  $\alpha$  is an over dispersion parameter.  $\alpha = 0$  implies Poisson.

	(1)	(2)
Variable	OLS	2SLS
LRPRICE	0.053	0.042
Long-run price	(2.52)	(1.60)
SD%CHPRICE	-0.100	-0.105
Price Volatility	(-2.32)	(-2.46)
%CHINDP	0.045	0.045
Growth of INDP	(2.38)	(2.44)
SD%CHINDP	-0.083	-0.095
INDP Volatility	(-1.72)	(-1.82)
CD	0.070	0.067
Cumulative Discoveries	(6.11)	(4.93)
$\mathrm{CD}^2$	-0.0002	-0.0002
CD Squared	(-6.45)	(-5.94)
CONSTANT	-3.29	-2.16
	(-1.60)	(-0.71)
$R^2$	0.27	0.27
p–values for H0:		
Exogeneity		0.66
Weak instruments		0.00
Overident. Restrictions		0.53

Table 3: OLS and 2SLS Entry Equations with Depletion, Baseline Model

The dependent variable is the number of mines entering each year. t statistics are shown in parentheses.

Robust standard errors are used.

Instruments for copper price: prices of lead and pig iron. Full sample, 1835–1986.

	(1)	(2)	(3)
	Secondary	International	International
Variable			2SLS
LRPRICE	0.020	0.016	0.092
Long-run Price	(2.42)	(2.14)	(2.01)
SD%CHPRICE	-0.054	-0.069	-0.087
Price Volatility	(-2.45)	(-3.21)	(-2.03)
%CHINDP	0.022	0.024	0.029
Growth in INDP	(2.16)	(2.56)	(1.54)
SD%CHINDP	-0.035	-0.136	-0.143
INDP Volatility	(-0.91)	(-4.04)	(-1.80)
CD	0.032	0.032	0.144
Cumulative Discoveries	(4.27)	(5.84)	(2.39)
$\mathrm{CD}^2$	-0.0001	-0.0001	-0.0003
CD Squared	(-3.73)	(-7.47)	(-2.78)
QS/QP	-0.0026		
US Secondary/Primary Prod	(-0.18)		
IMP/CONS		0.043	-0.002
Imports/Consumption		(4.05)	(-0.05)
CONSTANT	-1.51	-0.377	-12.1
	(-1.67)	(-0.45)	(-2.25)
log pseudolikelihood	-278	-272	
$\mathbf{R}^2$			0.42
$\alpha$	0.445	0.360	
	(3.67)	(3.29)	
p-values for H0:			
No serial Correlation		0.174	
Weak instruments			0.00
Overident. Restrictions			0.23

Table 4: Negative Binomial and 2SLS Entry Equations With Related Sectors

The dependent variable is the number of mines entering each year.

z scores are shown in parentheses.

Robust standard errors are used.

Years: 1835–1986, equations (1) and (2), 1880–1986, equation (3).

 $\alpha$  is an over dispersion parameter.  $\alpha=0$  implies Poisson.

Instruments for IMP/CONS: World production and growth in world production

	(1)	(2)	(3)	(4)
	Steam	Froth	SX-EW	All three
Variable	shovel	flotation		
LRPRICE	0.015	0.022	0.023	0.017
Long-run Price	(2.16)	(3.29)	(3.58)	(2.47)
SD%CHPRICE	-0.054	-0.043	-0.050	-0.057
Price Volatility	(-2.91)	(-2.49)	(-2.69)	(-2.94)
%CHINDP	0.025	0.024	0.024	0.025
Growth in INDP	(2.71)	(2.31)	(2.39)	(2.72)
SD%CHINDP	-0.071	-0.054	-0.086	-0.092
INDP Volatility	(-2.53)	(-1.63)	(-2.63)	(-2.51)
CD	0.030	0.032	0.032	0.030
Cumulative Discoveries	(5.46)	(5.22)	(5.51)	(5.17)
$\mathrm{CD}^2$	-0.00009	-0.00008	-0.00008	-0.00008
CD Squared	(-7.75)	(-4.99)	(-5.74)	(-5.18)
DOPEN	0.946			0.810
Steam Shovel	(2.71)			(2.39)
DFROTH		0.208		-0.106
Froth Flotation		(0.43)		(-0.27)
DSXEW			-0.949	-0.683
SX-EW			(-2.44)	(-1.63)
CONSTANT	-0.733	-1.672	-1.553	-0.774
	(-0.87)	(-2.06)	(-1.96)	(-0.93)
log pseudolikelihood	-276	-278	-276	-275
α	0.414	0.449	0.424	0.403
	(3.73)	(3.94)	(3.89)	(3.70)

Table 5: Negative Binomial Entry Equations with Technology Variables

The dependent variable is the number of mines entering each year.

z scores are shown in parentheses.

Robust standard errors are used.

 $\label{eq:Full sample, 1835-1986} Full \ sample, \ 1835-1986.$ 

 $\alpha$  is an over dispersion parameter.  $\alpha=0$  implies Poisson.

	(1)	(2)	(3)	(4)
	US Only	US & Mexico	US Only	US & Mexico
Variable			Panel	Panel
LRPRICE	0.016	0.017	0.026	0.027
Long-run Price	(2.01)	(2.13)	(3.64)	(3.82)
SD%CHPRICE	-0.048	-0.040	-0.018	-0.001
Price Volatility	(-2.10)	(-1.76)	(-0.79)	(-0.06)
%CHINDP	0.021	0.020	0.039	0.038
Growth in INDP	(2.13)	(2.09)	(3.56)	(3.43)
SD%CHINDP	-0.033	-0.030	-0.021	-0.014
INDP Volatility	(-1.08)	(-1.00)	(-0.60)	(-0.39)
CD	0.028	0.026		
Cumulative Discoveries	(4.81)	(4.39)		
$CD^2$	-0.00008	-0.00007		
CD Squared	(-5.31)	(-4.94)		
CDREG			0.046	0.038
Regional CD			(3.52)	(2.90)
$CDREG^2$			-0.0003	-0.0002
Regional CD Squared			(-3.72)	(-3.08)
MM	0.108			
Entry of Major Mines	(2.74)			
MMMEX		0.127		
MM with Mexico		(2.98)		
MMREG			0.346	
Regional Entry, Major Mines			(3.56)	
MMRMEX				0.450
Regional MM with Mexico				(4.39)
DAZ			1.332	1.012
Dummy for Arizona			(3.99)	(3.03)
CONSTANT	-1.15	-1.19	-3.491	-3.665
	(-1.30)	(-1.39)	(-4.24)	(-4.43)
log pseudolikelihood	-275.8	-275.3	-332.9	-329.5
$\alpha$	0.411	0.392	1.18	1.06
	(3.70)	(3.48)	(4.16)	(4.02)

Table 6: Negative Binomial Entry Equations with Expectational Variables, Aggregate and Panel

The dependent variable is the number of mines entering each year. z scores in parentheses. Robust standard errors. Full sample, 1835–1986.  $\alpha$  is an over dispersion parameter.  $\alpha = 0$  implies Poisson.

	(1)	(2)	(3)	(4)
	OLS	OLS	2SLS	2SLS
Variable	CR4	CR8	CR4	CR8
LRPRICE	0.071	0.063	0.132	0.105
Long-run Price	(0.99)	(0.88)	(2.38)	(2.17)
SD%CHPRICE	-0.089	-0.090	-0.073	-0.070
Price Volatility	(-1.61)	(-1.64)	(-1.26)	(-1.23)
%CHINDP	0.011	0.013	0.005	0.010
Growth in INDP	(0.54)	(0.69)	(0.30)	(0.56)
SD%CHINDP	-0.188	-0.200	-0.190	-0.216
INDP Volatility	(-2.33)	(-2.47)	(-2.31)	(-2.46)
CD	-0.073	-0.036	0.031	0.020
Cumulative Discoveries	(-0.30)	(-0.15)	(1.03)	(0.60)
$\mathrm{CD}^2$	0.00002	-0.00005	-0.0002	-0.0002
CD Squared	(0.05)	(-0.13)	(-2.94)	(-2.90)
CR4	0.054		0.092	
4–firm CR	(2.46)		(2.05)	
CR8		0.068		0.120
8-firm $CR$		(2.46)		(1.98)
CONSTANT	18.77	12.29		
	(0.49)	(0.33)		
$\mathbb{R}^2$	0.37	0.36	0.35	0.34
p–values for H0:				
Weak instruments			0.00	0.00
Overident. Restrictions			0.87	0.75

Table 7: OLS and Two Stage Least Squares Entry Equations with Concentration Ratios

The dependent variable is the number of mines entering each year.

t statistics are shown in parentheses.

Robust standard errors are used.

Years: 1911–1986.

Instruments for CRn: Changes in U.S. antitrust laws.















