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An empirical study of mine closings

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by

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In this paper, we study a well-known real option: the opening and closing of mines. Using a new database that tracks the annual opening and closing decisions of 285 developed North American gold mines in the period 1988-1997, we confirm many of the predictions from real options models. In particular, the probability that a mine is open is related to market-wide factors (including the level and volatility of the gold price and the level of interest rates) as well as to mine-specific factors (including the mine's fixed costs, variable costs, and reserves.) These results are both statistically significant and economically material. There is strong evidence of hysteresis, which would result from non-zero opening and closing costs. Together, the data provide strong support for the real options model as a useful descriptor of mines' opening and shutting decisions. In addition, we find that the decision whether to shut a mine is related to firm-specific managerial factors not normally considered within a strict real options model, most notably the profitability of other mines in the firm's portfolio and of the firm's other businesses. These relationships do not seem to be based on geographic synergies and we suspect they are an indication of capital allocation processes within these firms.

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I. Introduction

When the Royal Swedish Academy of Sciences announced the award of the Bank of Sweden Prize in Economic Sciences to Robert C. Merton and Myron Scholes, the official announcement noted the relevance of option pricing theory in analyzing real options, or projects with substantial option-like flexibility. In the quarter century since the publication of Black, Scholes, and Merton's seminal papers, there has been considerable research in the field of real options, especially as applied to natural resource industries. The concept of real options has been applied to managerially-important decisions (for examples, see Myers (1977) and Kester (1984)), techniques for valuing stylized real option projects have been established (see Brennan and Schwartz (1985a,b)), and real option techniques have been applied to value projects (for example, see Paddock, Siegel and Smith (1988)). Textbooks by Dixit and Pindyck (1994), Trigeorgis (1996), and Amram and Kulatilaka (1999) provide a summary of the state of the field.

However, empirical research on real options has lagged considerably behind these conceptual and theoretical contributions to the literature. This research has included applications of real options (Paddock, Siegel and Smith (1988)), evidence of real options explaining asset prices (Quigg (1993), Berger, Ofek and Swary (1996), and Davis (1996)), and evidence that real option models may help explain firm's risk exposures (Tufano (1998a)).

In this paper, we study direct evidence of real options. How often do they get exercised? By what types of firms? Under what circumstances? How do managerial concerns affect the exercise decision? We study the "classic" real options held by gold mining firms; the right to open and shut a mine in response to output prices, as modeled by

Brennan and Schwartz (1985a). The advantage of studying mine closings and re-openings is that they are discrete and economically-material events, and thus we can collect information on them.[1]

Our work is close in spirit to Kovenock and Phillips (1997), who study plant closings in ten industries using detailed plant-level and firm-level data.[2] Like them, we study the plant-level decision of whether to cease operations. However, we seek to explicitly study the real option to close in response to commodity price fluctuations, rather than the impact of strategic interactions on the exit decision.[3]

Our work is also related to empirical inquiries into corporations' decisions to call convertible bonds. Theory posits that firms should call convertible bonds as soon as they are in-the-money (Brennan and Schwartz (1977) and Ingersoll (1977a)). Early empirical research probed whether firms followed this prediction and concluded that corporations followed suboptimal exercise behavior; subsequent work reconciled this seeming anomaly (see Ingersoll (1977b), Mikkelson (1981, 1985), Asquith and Mullins (1991) and Asquith (1995)). We too seek to directly inspect the exercise behavior chosen by firms to examine the predictive content of option theory.

The bulk of this research project (Sections II through IV in this paper) examines whether economic flexibility is material and well described by the real options model. Section II summarizes hypotheses about optimal closing decisions that are derived from the real options model of Brennan and Schwartz (1985a). Section III describes our data, a newly constructed database of North American gold mine activity, and includes an extended discussion of estimation of firm cost structures, an important input to the real option model. Section IV reports the main empirical results of the paper, which show that the predictions of the real option model are borne out strongly in the closing and opening behavior of mines.

The real options model is a "reduced form" model in the sense that any "non-economic" factor that leads to inaction could be recast as a "closing cost" under the model. In Section V of the paper, we examine whether closure decisions differ between single-mine vs. multi-mine firms, whether profitability of other firm activities affects the closure decision, whether organizational and mine ownership structure affect the decision to close, and whether community concerns might affect the closing decision. In Section VI we summarize and conclude.

II. Real options theory and mine closings

Brennan and Schwartz (1985a) provide a formal economic model of the decision to open and close a mine in the context of real options theory. In particular, they analyze the stochastic optimal control problem where a firm may temporarily close a mine in response to the market price of the mine's output.[4] The mine can be in one of three states: open, temporarily shut (closed) or permanently abandoned. Closed and abandoned mines differ in that the former incur a fixed maintenance cost and can be reopened at some cost.

The real options approach suggested by Brennan and Schwartz is not the only economic analysis of this class of problems. The key insight of their approach is to stress the functional equivalence between the mine and a portfolio of traded claims that allows one to replicate the untraded mine with traded assets. Other researchers employ similar mathematics, but analyze the problem from the perspective of firms that act as if they were risk-neutral.[5] Still others use decision-analytic models to model these choices, in which utility is an explicit input variable.[6] Our empirical tests are unable to distinguish among these various economic models of managerial flexibility, but will use the real options model of Brennan and Schwartz as representative of this class of models. We try to distinguish between this class of models and “dynamic DCF” models, where managerial decisions to proceed or halt an investment are revised every period by performing static DCF calculations and using the simple positive-NPV rule to make a decision. Because volatility does not affect the investment decision in these simpler models, its economic significance in our empirical work informs us about the relevance of real-option-like models.

Predictions from real options models about threshold levels. In their own words, one of Brennan and Schwartz’s goals was to “provid(e) a rich set of empirical predictions for empirical research” (p. 154). While the model can be used to value mining projects, it can also be used to predict the decision rules that govern when mines would be closed or reopened. These predictions can be framed with respect to the latent threshold mineral prices at which a firm would close an operating mine (s_1) or reopen a closed mine (s_2).

We can relate these thresholds to the Markov probabilities that a closed mine would be reopened or that an open mine would be closed over some time period, conditional on its current state. Suppose that the future distribution of mineral prices is represented by the probability distribution in **Figure 1**, and that the latent opening and closing thresholds are represented by s_1 and s_2. At the current mineral price, the probability that an open mine would stay open in the next period is represented by the areas B plus C, and probability that it would be closed is A. If the mine was currently closed at the current spot price, the probability that it would be open in the next period is the area in region C, and the probability that it would stay closed is A plus B. In the regions A and C, the mine would be sure to be closed and open, respectively. However, in the region B, it would continue in its operating state from the prior period. This difference demonstrates the hysteretic path-dependency of the real option decision.

We can easily translate the comparative statics of threshold prices into the comparative statics for the likelihood of a mine being open or closed.[7]

1. *Prior state.* The probability that an open mine will stay open is larger than of a closed mine reopening, and the probability that a closed mine will stay closed is larger than of an open mine closing.
2. *Metals prices.* As the current metals price increases, the probability that an open mine will stay open increases and the probability that a closed mine will reopen increases. While the optimal boundaries are not a function of the current metals price, higher prices make it more likely that both thresholds are exceeded.
3. *Volatility.* As the volatility of the mineral price increases, there are two forces at work. First, increasing the volatility changes the thresholds; with higher volatility, decision makers would want to be more certain before spending the opening and shutting costs, thus the thresholds are pushed outwards. However, increasing the volatility also changes the distribution of metals prices and increases the "tail probabilities." Even though these two forces work in opposite directions, the comparative statics indicate that the former effect dominates. Thus, as volatility increases, the probability that an open mine will stay open increases, and the probability that a closed mine will reopen decreases.[8]

4. *Operating costs.* As annual operating costs increase, the probability that an open mine will stay open decreases and the probability that a closed mine will open decreases.
5. *Shutdown costs.* As the costs of shutting increase, the probability that an open mine will stay open increases, and the probability that a closed mine will reopen decreases.
6. *Reopening costs.* As the costs of reopening increase, the probability that an open mine will stay open increases and the probability that a closed mine will reopen decreases.
7. *Maintenance costs.* As the costs of annual maintenance increase, the probability that an open mine will stay open increases and the probability that a closed mine will reopen increases.
8. *Reserves.* As the quantity of reserves increases, the probability that an open mine will stay open increases and the probability that a closed mine will reopen increases.
9. *Interest rates.* As the discount rate increases, the probability that an open mine stays open increases and the probability that a closed mine will reopen increases. Conversely, as the convenience yield on gold increases, the probability that an open mine will remain open decreases and the probability that a closed mine will reopen decreases.[9]

Table I, Panel A summarizes these predictions. Framing the predictions in terms of probabilities of opening and closing is useful in our research. We observe whether mines are open or closed, and use the variables above as predictors of this observed state using discrete choice models (See Maddala (1983)).

III. Description of the database of North American gold mines' activities

From the *Mining Journal*'s annual survey of mines (published through 1991) and from the 1997 version of its *Metallica 2000* database (which included data on mines through the end of 1996), we construct a list of all North American gold mining properties. To ensure that our results were not affected by survivorship bias, we augment the *Metallica* database for mines that were permanently closed in 1997 and which might not appear in the database. In addition, we hand-collect information on all mines for the year 1997 because a large number of closings occurred in 1997. In each year from 1988 through 1997, we collect information on the gold production, proven reserves,[9] operating costs, technology, and ownership of each mine. This information comes from a variety of sources, but the primary source is the Metallica database, which we augment with information from annual reports, press releases, and news stories.

Mining properties are classified as developed (or operational) or exploratory (i.e. the mine has not been developed to the point at which it could be operated.) We focus on developed mines, and their decision to be open or closed. Our sample universe includes 285 North American gold mines that were operational at some point during 1988-1997, and for which sufficient other data were available, as shown in **Table II**.

To identify whether a developed mine was open or closed at any point in time, we use a variety of information. First, the list of mines published through 1991 in the *Mining Journal* identified mines that were temporarily shut. Second, the *Metallica* database indicated mines that were temporarily inactive or permanently closed as of the end of 1996. Third, if a mine had a production of zero in any year, it either closed, or the information was not available. However, these screens proved inadequate in clearly identifying economic closings for a variety of reasons. If a mine closed for a few months in a given year then reopened before year end, it would not show up as closed based on any of these criteria.

A mine may close for many reasons: Reserves can be exhausted or flooding may bring production to a halt. Political unrest may make it impossible to operate the project. Inclement weather may temporarily stall an open-pit project. We focus on mine closings that are primarily "economic" in nature, in the sense that the owner of the mine chooses to voluntarily and temporarily shut a geologically-operational mine because it is no longer economic to operate it under current market conditions.[10] We also study mine re-openings, in which a firm voluntarily opens a previously-shut project in response to economic conditions.

To attempt to identify whether and why mines were open or closed, we searched Lexis-Nexis, the *Mining Journal* CD-ROM,[11] and firm financial statements to identify *whether* a mine had closed or reopened, *when* this closing (reopening) took place, and the *reason* given by the company for the closing.[12] Of the 285 mines in our database, 213, or 75%, had closed at least once, and of these 26 had reopened sometime after their temporary closing. Mine reopenings are defined when a closed mine resumes production.

Using company announcements or press reports, we categorize the stated reasons for closure as either: (1) economic closings, in which the firm states that the closing is the result of low gold price; (2) depletion of reserves; (3) weather and geology (e.g., flooding, fires); (4) strikes; (5) environmental closings (e.g., spills, man-made disasters) and (6) no reason given. These reasons and the number of mines in each category are given in **Table II,** including 86 “economic” closings and 10 “economic” re-openings in the sample.

For mine closings (or re-openings), we identify the closing date (and announcement) as precisely as possible. In some instances, the mine closing is announced in a daily news report and in these cases, we can identify the exact date of this closing announcement. In other instances, a story in a weekly or monthly periodical, a filed quarterly report, or an annual report merely indicated that the closing took place in a particular quarter or during the year.[13]

Independent variables. To test whether closings are well described by the real option model, we collect information on gold prices, volatility, interest rates, and the mine cost structure and prior state (open or closed).

Based on the closure date, we can describe the *gold price* environment in the period over which the closing (or reopening) decision was likely to have been made. Gold prices (in US $/ounce) are obtained from daily data provided by *Virtual Gold Research*.[14] We use the average of the morning and afternoon London fix as our daily gold price reference. *Volatility of gold returns* are calculated from the historical return series, where the return includes the daily 3-month gold convenience yield (also known as the "lease rate"). If the precise closure date is obtained, we calculate gold price from daily data for the previous year ending on the announcement date. If the closing can only be identified to within a month, we use the 15th of that month and work backwards. If the closing can only be identified within a year, we use the mid-point of the year as our calculation end-point.

For *discount rates*, we collect information on the average ten-year Treasury bond rate, obtained from *Datastream.* In some specifications, the model calls for the use of a *real* rate; to calculate the expected real interest rates, we subtract inflation expectations (taken from the Philadelphia Federal Reserve Bank Survey of Professional Forecasters) from the 10-year bond yield.[15] For the convenience yield on gold, we use the yearly average of the gold lease rate from *Virtual Gold Research*.

We also need information on mines' marginal and fixed costs, the expense of maintaining a mothballed mine, the cost of closing an open mine and the costs of reopening a closed mine. For each mine, we collect information on annual average cash costs, which we obtained from the *Metallica* database, annual reports, press releases, and news stories from *Lexis-Nexis* or from the *Mining Journal CD*. While these costs are measured and possibly reported with error, they are the best data available from which to calculate cost structures.

Cash costs (c) are *average* costs and include both fixed and marginal components, but for our tests we need to distinguish these two cost components. Mineral economists have found that fixed costs are a function of the size of the remaining reserves R (in ounces) and the technology of the mine which we represent by T, a dummy variable equal to 1 if the mine is underground, and 0 if it is a surface (open pit) mine.[16] Marginal costs are a function of both the current level of production (q, or throughput), the cumulative amount of mineral already extracted (which would be inversely related to the remaining reserves R), and the mine technology. To capture the effect of the remaining reserves on the variable cost, we create a set of dummies D_R corresponding to reserve quartiles, and we interact them with the production variable q. Thus, to decompose total mining costs into fixed and variable components, we estimate the following cost function:[17]

$$cq = a_0 + a_1 R + a_2 T + b_0 q + b_1 qT + S b_i D_i q \qquad (1)$$

From this regression, the β parameters represent the marginal mining costs of a unit of gold production, and the α parameters reflect fixed (or per period costs) that are independent of the level of production. In principle, fixed costs estimate the costs of an operating zero-production (or temporarily closed) mine. While we recognize that these are imprecise estimates of the costs of maintaining a closed plant, we use them as a noisy proxy for these maintenance costs.[18]

Table III estimates equation (1) over the full panel of mines, as well as over two subsets of mines with similar technology characteristics. Columns A through D examine nominal costs, and column E analyzes deflated costs (in real 1988 US$). In general, our estimates of mine costs reflect the stylized facts advanced by mineral economists. Fixed costs are a function of reserves; base level fixed costs are about $1.3 million in the sample and rise about $2.4 per ounce of reserves. Thus, fixed costs for a mine with two million ounces of gold would be $6.2 million per year. Variable costs are higher for open pit mines, and are inversely related to reserve size, as predicted. From column D, which includes mine fixed effects and controls for the impact of reserves on marginal costs, we see that variable costs are about $265 an ounce for the smallest open-pit mines, but fall to $142 an ounce for the largest deep-shaft mines. We use the specification in column D of **Table III** to estimate predicted fixed and marginal costs for all the mines in our sample.[19]

The remaining variables of interest are the *costs of closing* and *reopening* the mine. We do not have direct information on these costs. Mining engineers have given us broad estimates of the range of these costs and have suggested that they are proportional to the type of mine and its capitalized cost of construction, which we consider (as well as to the length of the time the mine is anticipated to be closed, which we do not measure).[20] To capture the fact that closing and reopening costs for underground mines are higher than for open pit mines, we include a technology dummy variable to capture this effect. This variable equals one for underground mines, and zero for open pit mines, and it is interacted with the prior state dummy. To capture the observation that closing costs might be proportionate to initial capital costs, we include capitalized costs of the mines (expressed in 1996 US $) in our analysis.

IV. Empirical results

If mining managers act in accordance with the real option model, then the decision to open or close will be related to the economic characteristics of the mine as well as to the market conditions, as summarized in **Table I,** Panel A. In this section, we test whether these factors are related to the decisions whether to close North American gold mines in the period 1988-1997.

It is sensible to articulate what the null hypothesis is—and is not—in our analysis. As we mentioned in Section II, while the real options model provides predictions about mine openings and closings, other economic models provide similar predictions. For example, optimal stopping time or decision-analysis models were applied to this class of problems before the real options literature was written and many produce similar comparative statics. Simpler models of managerial flexibility would be "dynamic DCF" models, where managerial decisions to proceed or halt an investment are revised every period by performing static DCF calculations and using the simple positive-NPV rule to make a decision. We *can* empirically distinguish between this simpler class of models and the real options class of models because dynamic DCF models would not explicitly include volatility as a variable affecting the decision to close.

As a precursor to more formal analysis, **Figure 2** and **Table IV** relate mine closings to the price of gold and to the characteristics of mining firms. Under the real options model, the probability that a mine will be open will be is positively related to the gold price and will display hysteresis. In **Figure 2,** we plot the time series of monthly average gold price and percentage of mines closed for economic reasons over the period 1988-1997. As the gold price fell from about $470/oz to $330 an ounce from 1988 to 1993, the percentage of operational, non-depleted mines closed for economic reasons rose from 4% to 16% of all mines. Economic closures were not immediate, as hysteresis would suggest. Although gold prices recovered through late 1995, few mines reopened, as would be expected with hysteretic behavior. Finally, as the price began to drop again in 1996 and 1997, more mines closed, with about 20% of all mines closed for economic reasons by the end of 1997. The significant inverse correlation between the gold price and the percentage of mines closed for economic reasons (ρ = -0.81) and the slow adjustment to prices are quite consistent with behavior predicted by the real options model.[21]

In **Table IV**, we report descriptive statistics on mines that closed for economic reasons at some point in the period 1988-1997, mines that closed for other reasons in this period, and mines that never closed. These univariate results are consistent with common sense and with the predictions of the Brennan and Schwartz model: Mine closings are more likely among high-cost producers. Mines with economic issues have average cash costs 12% higher than mines that never closed, and their gross margins are $27/oz lower. These differences are statistically significant.

The Brennan and Schwartz model also predicts that firms with higher maintenance costs (which we proxy with fixed costs) would be more likely to remain open. The table suggests that mines that never closed have fixed costs nearly 50% larger than mines that did close at some point for economic reasons. Similarly, the model predicts that firms with greater reserves should be more likely to stay open, and the univariate analysis in **Table IV** shows this: Mines that closed had reserves 45% smaller than mines that never closed. These univariate results—in conjunction with the time series trend in closings shown in **Figure 2**—are generally consistent with the notion that mining managers' open/close decisions seem well predicted by the real options model. However, to the extent that capitalized costs and the underground technology are proxies for higher closing costs, then the univariates do not suggest that mines that close had lower closing costs as predicted.

To conduct a more formal examination of this concept, we employ probit multivariate discrete-choice models, with the mine state as the observed (dependent) variable and the regressors in **Table I** as the independent variables.[22] We also include a dummy variable indicating if the mine was open in the *previous* year because the model suggests that the probability of opening and closing is conditioned on its previous state. **Table V** shows the results of the probit regressions for a variety of specifications, with the reported coefficients reflecting the marginal effects of each coefficient evaluated at the sample means. Panel A shows the results for standard probit regressions, while Panel B presents the results using a random effects probit specification, as suggested by Pendergast *et al.* (1996) to correct for contemporaneous correlation in mine closing decisions.

Panel A, column A show the simplest specification, modeling the probability of a mine being open as a function of only the gold price and the mine's prior state. The coefficients on both variables are of the predicted sign and statistically significant. The probability of a mine being open increases with gold price and the probability of being open is higher if the mine was open on the previous year.

To depict the impact of gold prices on the likelihood of a mine being open or closed, we can the plot marginal probability of being open as a function of the independent variables (see Greene (1997), chap. 19). **Figure 3** plots the likelihood from the probit model that a mine will be open, conditional on its prior state and the gold price, evaluating the non-gold price variables at the sample mean. The gold price is graphed along the horizontal axis, and the two figures show the probability that a mine would be open for mines open or closed the prior year. Panel A shows the probabilities for the sample of all mines; Panel B reports the probabilities for a subsample of mines that closed at some time.

The hysteretic behavior of mine openings and closings is readily apparent by the difference between the two plots in each figure. For example, in Panel B, if the mine was previously closed (dotted line) the probability of the mine being open rises from zero at a gold price of $280/oz, to 100% at a price of about $720/oz. However, if the mine was already open (solid line) the probability of the mine remaining open is positive even at gold prices of about $220/oz. This hysteretic effect is clearly predicted by real options models.

Panel A, column B of **Table V** adds gold price volatility to the prior specification. As discussed earlier, the real option model predicts that higher volatility should make an open mine more likely to stay open, but make a closed mine less likely to reopen. Therefore, we analyze the impact of volatility on previously-open and previously-closed mines separately. The results in the table are consistent with the predictions of the model. Increasing volatility is positively related to the probability that an open mine will remain open, significant at the 10% level or better in all but one specification in the table. . For closed mines, increasing volatility is negatively related to the probability of being open in the next year, although this result is statistically insignificant. Consistent with the Brennan and Schwartz model, BRMR (Binary Response Model Regression) specification tests (Davidson and MacKinnon (1993), Chapter 15) indicate that the inclusion of volatility improves the specification of the model.

Panel A, column C adds predicted nominal fixed and marginal costs to the specification.[23] As variable costs of operation increase, a mine should be less likely to be open, and as maintenance costs increase, it would be more likely to be open. The results support this prediction. The coefficient on marginal costs is negative and significant in all specifications (for the full sample), and the coefficient on fixed costs, which is a proxy for maintenance costs, is positive and significant in all specifications.[24] Once again, BRMR specification tests indicate that the inclusion of fixed and marginal costs (or reserves, in column D), consistent with the real options model, statistically significantly improve the specification of the model.

Panel A, column D shows the effect of increasing reserves on the likelihood of the mine being open. As predicted, increasing reserves implies a higher probability of an open mine, and this result is statistically significant. Unfortunately, we cannot jointly specify reserves and costs as regressors, because in our cost model, fixed and marginal costs are linear functions of reserves, leading to perfect multicollinearity.

Panel A, column E adds interest rates to the specification. Nominal interest rates are strongly related to the decision about whether or not a mine is open. As predicted, when interest rates are higher, mines are more likely to stay open. (There is no apparent empirical relationship between convenience yields and the probability of a mine being open.) However, when we include interest rates, the decision whether or not to close is no longer dependent on the price of gold, which runs counter to our earlier results, to the real option model and to our strong priors about how managers make decisions regarding mine closings.

This apparent anomaly is likely to be the result of two factors. First, in the period studied, annual gold prices and nominal interest rates were strongly positively correlated ($\rho = 0.60$). With this strong multicollinearity, it is difficult to disentangle the effects of gold prices and nominal interest rates on the closure decision. However, given that the panel uses data over a ten year horizon, it is possible that using nominal values is inappropriate. Brennan and Schwartz (1985a, pp. 144-145) consider the impact of inflation on the real option decision, and derive results using deflated values of costs and real rates. We use deflated values in column F, along with real interest rates. Deflated costs are obtained from **Table III**, column E, where we use the Producer Price Index to adjust the average cost numbers, and from these estimate deflated marginal and fixed costs. The gold price in column F is also deflated by the PPI. Finally, we estimate the real interest rate as equal to the nominal rate less inflation expectations (as described earlier). Panel A, column F, of **Table V** shows that using this deflated specification, real rates have a significant positive association with the likelihood that a mine is open, as predicted. Furthermore, under this specification, deflated gold prices also have a significant positive relationship with the likelihood of being open, as predicted and as we see in columns A through D.[25] To support these results, BRMR specification tests on Columns E and F indicate that nominal interest rates are not omitted variables.

We also ran the regressions adding capitalized costs and the mine technology dummy as measures of closing and reopening costs. As these costs increase, open mines should be more likely to stay open and closed mines should be less likely to be open. Unfortunately, we lose almost half of the observations in the sample when using capitalized costs, as this data is not always available. For those mines where capitalized cost information is available, there is no relationship between these costs and whether the mine is open or shut. Nor does the coefficient on mine technology have a statistically significant relationship with the probability of being open. These results (not shown) indicate either that the costs of closing and reopening are not important in the decision of whether to close a mine, or, more likely, that our measures are poor proxies for the unobserved closing costs.

From the probit results we can assess the economic significance of the effects described earlier. Working from **Table V,** Panel A, column C, we calculate the probabilities that a mine would be open, using mean values for all significant variables. A mine that was open in the prior year is 90.2% likely to be open in the current year, and a mine that closed in the prior year is 11.0% likely to be open in the current year. For mines with fixed costs one standard deviation above the mean, the probabilities of being open jump to 99.5% and 25.0% (for previously open and closed mines, respectively). For mines with variable costs one standard deviation above the mean, the probabilities of being open fall to 62.4% and 9.2% respectively. Reserve size has a large impact on the probabilities of being open, especially for previously closed mines; for a one standard deviation increase in reserves, the probabilities of being open rise to 99.9% and 91.0% respectively.[26] When volatility rises one standard deviation from the mean, the probability of an open mine remaining open increases slightly to 97.0%. Finally, for a $10 higher gold price, the probabilities of being open increase modestly, to 96.3% and 12.1% respectively.

Robustness tests and predictive power. To test the robustness of these results, we carry out a number of additional tests. Mine openings and closings are contemporaneously correlated, therefore it may be inappropriate to assume independent, homoskedastic residuals. An approach suggested in the literature (Pendergast *et al.* (1996)) to correct for contemporaneous correlation is the use of a random effects model. In Panel B of **Table V** we re-run the regressions of Panel A with a random effects specification. In general, the random effects decrease slightly the explanatory power of the tests without substantially changing the values of the coefficients. This indicates that the original specification of Panel A without correction for contemporaneous correlation is adequate.

The hysteresis we observe could be a result of misclassifying abandoned mines as being temporarily closed.[27] If closed mines were truly abandoned (and not able to be reopened by definition), then we would observe hysteresis in that these "closed" mines would never reopen. While we can identify depleted mines as abandoned by removing them from the analysis once closed and depleted, we do not have a means to identify non-depleted, but "abandoned" mines.[28] To diagnose whether this factor might explain our results, we reran the analyses in **Table V** after removing undepleted mines that produced no gold for at least two years in a row. This stringent filter removed 46 mines from our sample. Our results (not shown to conserve space) were similar to those in **Table V**, with the key results unchanged. For example, the coefficient on the prior-open variable using the restricted sample was 2.03, with a *p*-value of 0.001. Thus, while there may be some misclassification of closed and abandoned mines, we think it cannot explain the hysteresis we observe.

Another issue concerns how the Markov states are incorporated into the probit specification. Our general specification assumes that the slope effects of the coefficients are the same for open and closed mines. To test whether the coefficients differ for open and closed mines, we include interaction terms for all regressors and use a Wald test to determine whether the slope coefficients are the same. We cannot reject the hypothesis that the coefficients in both states are equal for all explanatory variables, except for the gold price. The coefficient on gold price if the mine is closed is not statistically significant for all specifications except the specification in column A. Economically, this suggests that there is no impact of the gold price on the probability of a closed mine reopening. This non-result probably reflects the fact that there were few re-openings in the period we studied despite the strengthening of the gold price in the mid-1990s.

We have seen that mine closing and opening behavior is broadly consistent with real options theory, at least with regard to the direction of the effects of the postulated independent variables on the probability of mine opening and closure. Stronger and more convincing evidence can be provided in support of the real options models if not only the *sign*, but also the magnitude of the effects were consistent with real option models. To explore this question, we simulate the real options model using Monte-Carlo, where the random variables are the independent variables, which are distributed according to the previously-determined probability densities extracted from the sample data. We do not have the opening and closing cost data, so we determine *what* implied values of the opening and closing costs are consistent with the observed opening and closing probabilities, and verify whether or not those values are reasonable.

We assume that the opening and closing costs are proportional to production, and attempt to estimate these costs in dollars of cost per ounce of production (See Slade (2000)). Unfortunately, under the Brennan and Schwartz (1985) model, there is no set of opening and shutting costs that uniquely map back to opening and closing thresholds or probabilities. For our data set, we find that closing costs of $0.00 per ounce and opening costs of $25.07 per ounce generate opening and closing probabilities consistent with the empirical data. If we constrain the opening and closing costs to be equal, we find that opening/closing costs of $12.41/ounce are consistent with the empirically- obtained probabilities. For the average mine in our sample, which produces 66,500 ounces per year, this latter calculation estimates opening and shutting costs of about $826,000. This estimate is in the same order of magnitude as those we received informally from mining engineers, although they profess that the range of costs is very wide.

As an additional robustness check and measure of predictive power of the real options model, we carried out out-of-sample prediction tests from estimated in-sample coefficients following the methodology of Henriksson and Merton (1981).[29] The basic approach is to use data for the years 1988-1996 to estimate the probit regression coefficients. We then use these in-sample estimated coefficients to calculate the opening and closing probabilities of each mine for 1997. If the calculated probability for 1997 is greater than a breakpoint of 50%, then the mine is predicted to be open. If the probability is less than 50%, the mine is predicted to be closed. We report the results for **Table V**, Panel A, column C using this 50% breakpoint, although the results for other specifications and breakpoints were similar.

As a first set of tests, we test our model against the null hypothesis that the best predictor for mine state in 1997 is its state in 1996. While the real options model had better predictive power (it made the "correct" forecast 93% of the time versus 70% of the time for the null predictor), we are unable to statistically distinguish (either with chi-squared tests (Green (1997)) or with Henriksson-Merton tests) between the real options model and this naive prediction. This result is apparent from **Table V**, where the last-year dummy coefficient has the largest economic impact.

In order to separate the statistically-dominating effect of previous year state on the predictive power of the real options model, we repeated the tests using the prediction for the *change* in mine state. In this case, if the model predicted *no change* in mine state in 1997 from its state in 1996 (i.e. closed mines are predicted to remain closed, or open mines are predicted to remain open) the prediction was given the value 0. If the model predicted a *change* in mine state, the prediction was given the value 1. The null hypothesis is that of *no change* for any mine, and thus always has the value 0. Under this specification, the real options model was a significantly better predictor than the null predictor to better than 0.1%.

Finally, to understand the marginal explanatory contribution of volatility and cost structure, we tested alternative model specifications where we left out volatility, or used average costs instead of fixed and marginal costs. These reduced alternative specifications were substantially poorer predictors than the full real options specifications. Volatility and marginal costs provide sufficient additional explanatory power in these Henriksson-Merton tests. This is evidence that volatility is a highly relevant decision variable for the mine closing or opening decision: Managers are apparently going beyond static or dynamic DCF formulations (which are independent of volatility) when making operating decisions. This result corroborates our more formal BRMR specification tests carried out earlier.

Summary. Our results indicate that managerial flexibility is a material corporate event, and that real options theory developed over the past two decades can be used to explain the pattern of closing and re-opening decisions. The real option model provides a rich set of predictions regarding the circumstances under which mines would be closed and reopened. Many of these predictions are borne out. The exercise decision is dependent on the price of gold in that higher gold prices increase the likelihood that mines will be open. Furthermore, opening and closing displays strong hysteretic behavior, in that the likelihood of a mine being open (or closed) is strongly affected by its operations in the prior period. For the most part, the costs of operating an open mine, maintaining a closed mine and closing/reopening affect the decision as predicted. Volatility matters in the opening and shutting decision. Finally, the economic significance of these variables in explaining the decision to shut mines is material, and of the order of magnitude predicted by the real options model.

V. Managerial influences on the opening and shutting decision.

As we note in the Introduction, the real options model is a reduced-form model. Any factor that makes it likely that managers will close a mine can be reinterpreted as affecting the costs of operation, maintenance, shutdown or reopening. For example, psychologists and sociologists study the impact of personality traits and organizational designs on organizational inertia, which in this case would be hysteresis in closing (and reopening) mines.[30] If there is a systematic relationship between these "non-economic" factors and the closing decision, one could recast the psychological or sociological factors as "effective" closing costs. Our goal in this section of the paper is to begin to examine how various managerial factors—including portfolio effects, the need to negotiate with co-owners, and stakeholder concerns—affect mines' closing and opening decisions.

Brennan and Schwartz's work takes the mine as the unit of analysis, as if it were a stand-alone unit. However, most mines in North America are parts of mining companies with *portfolios* of mining and non-mining assets. Recognizing that firms may take their profitability at *other* locations into account when deciding whether to close a particular mine, we study spillover effects on the decision to close a mine. Second, their analysis assumes that a single firm owns a mine, but in practice many mines are jointly owned and operated by several companies. Given that material corporate decisions must be *negotiated* by these parties, we examine whether the requirement to coordinate decisions might slow down decision making. Finally, most models of "economic" decision-making leave little room for the impact of various *stakeholders* on the closing decision, although mine closings can have a large impact on communities in which mines and their managers live. We study whether managers seem to take these stakeholder concerns into account when the communities they affect are ones in which they live.

Portfolio effects and the costs of closing a mine: Consider two otherwise-identical mines with the same geology and cost structure, but which have different owners. One is part of a large firm with many mines and the other is a stand-alone mine. While the "technical" costs of opening and shutting the two mines may be identical, the two firms might not behave the same when deciding whether or not to shut a mine.

If the multiple-mine firm closes the mine, it can move managers to other projects or mines within the firm. However, the solo-mine firm would not be able to transfer the managers elsewhere, and would have to furlough its managers, who might find other jobs elsewhere and be difficult to rehire. Furthermore, the mine manager in a solo-mine firm might have greater decision rights regarding closure than a mine manager in a larger entity. For these two reasons, one might think that solo-mine firms might be more reluctant to close mines than would multi-mine firms. However, working in opposition to this force, the solo-mine firm has no other operations to cross-subsidize a poorly-performing mine, and might be more likely to close its mine.

To test whether solo-mine firms make different shutting decisions than multi-mine firms, we collect information on the number of mines owned by each of the firms in our sample in each year. This data was collected from Metallica 2000, the IDD Mergers and Acquisitions Database, press reports, and financial statements. **Table VI** shows that the average firm in our sample owns 3.0 mines, but that 42% of the mines are owned by a solo-mine firm.[31] We create a dummy variable equal to one if the firm has interests in only one mine and zero if it has interests in more than one mine, and we interact this dummy variable with the prior state variable (which equals one if the mine were open in the prior year). To the extent that solo-mine firms were less (more) likely to close, we would expect that the coefficient on this interaction term would be positive (negative).

It is unpleasant to close mines and lay off workers, and we assume that most managers would prefer not to carry out this decision. This might be most possible when the poorly performing mine was "hidden" inside an otherwise profitable organization. For example, a multi-mine firm making positive average profits across the whole portfolio of mines might tolerate a money-losing mine longer than another firm whose other properties had higher costs. Similarly, a diversified firm might use profits elsewhere to mask losses in a mine, and be slower to close a high-cost mine.[32] These spillover effects have been demonstrated in diversified firms. For example, Lamont (1997) and Shin and Stulz (1996) show that investment decisions in multi-divisional firms are affected by the profitability of other divisions, with investment in smaller divisions cut as cash flow in larger divisions is reduced.

To test whether the profitability of *other* businesses affect the decision whether to close a particular mine, for each firm we calculate the weighted average variable costs of production of the "other" mines in its portfolio, using reserves as weights, or for partial owners, the fraction of reserves owned. Variable costs represent the predicted marginal costs from **Table III,** specification D. Thus, if a firm has ten mines, for each mine we calculate the average variable costs of the other nine mines it owns. If a firm has no other mines, this variable equals the mean marginal cost for all mines in the sample.[33] We interact this *other mine cost* variable with the prior state variable; if multi-mine firms whose other properties have lower costs are less likely to close down a particular mine, this interaction term would have a negative coefficient (i.e., an open mine would be more likely to stay open when the other properties have low costs.) We also calculate the *fraction of firm reserves* accounted for by each particular mine and interact this variable with the prior state dummy variable. To the extent that firms let relatively smaller mines stay open but more carefully scrutinize larger properties, this variable would have a negative coefficient (mines that represent a smaller fraction of reserves would be more likely to stay open.)

Table VII, Panel A, reports probit results on the impact of these three variables (solo mine, costs of other mines, and fraction of reserves in the current mine) on the decision to close, paralleling the presentation in **Table V,** Panel A**.** To conserve space, we do not show the specifications with interest rates or deflated prices. We consistently find that the activities of other mines seem to affect the decision whether to close the mine. Firms that own only one mine are less likely to keep that mine open, consistent with notion that multi-mine firms may be more likely to keep properties open. When the operating costs of the *other* mines are lower, firms are more likely to keep the current mine open. Finally, within multi-mine firms, smaller mines are less likely to be kept open than are mines that represent a larger fraction of the firm's reserves. Together, these results suggest that the decision to close a particular mine is a complex firm-level portfolio choice, related to the existence and profitability of other mineral properties.

These factors are economically meaningful. For example for the specification in column C, among previously-open mines, a solo-mine firm's mine is 37.3% likely to be open in the current year, but a multi-mine firm's mine is 65.0% likely to be open.[34] Among multi-mine firms, firms whose other mines have operating costs equal the sample mean are 96.2% and 13.4% likely to be open, respectively for previously-open and closed mines; if the operating costs of their other mines were one standard deviation higher, these probabilities would fall to 92.6% and 7.5% respectively.

This joint-decision-making may be the result of unobserved economies among the various mines. For example, mines may share a common processing or refining facility, and synergies would require that closing decisions be coordinated. Alternatively, the apparent cross-effects we observe could be the result of internal capital markets making decisions on the basis of average portfolio performance, rather than treating each project on a stand-alone basis. To look for evidence supporting the first possibility, we separate the *other mine cost* variable into costs for other mines in the same state (or province, in the case of Canada), and for mines outside the state of the mine-year under observation.

Our assumption is that in-state mines are more likely to share common milling or processing facilities and thus exhibit synergies that would call for coordination in the decision to close. If so, the coefficient on in-state costs would have a stronger impact on the decision to close than would out-of-state costs. We carry out likelihood ratio tests on the equality of the in-state and out-of-state *other mine cost* coefficient. We found that the two coefficients are not significantly different, indicating that the decision to close is not affected by the location of other mines owned by the same firm, and hence by location synergies.[35]

The mine-level portfolio measures used in Panel A of **Table VII** fail to capture potential sources of profits and cash flow that a firm might enjoy, including profits from non-gold businesses and gains from gold hedging contracts. To capture the profits that a firm might enjoy from its "other businesses," we include a crude measure of total firm profitability, lagged *return on assets*, in Panel B of **Table VII**. If firms with larger overall profits are less likely to close individual mines, we would expect a positive coefficient on this variable. We also include a proxy for firm size (the book value of assets) to see if larger firms were less likely to close their mines. Panel B suggests that firms with higher returns on assets are more likely to keep their mines open, although the result is economically modest. Firms whose ROAs are a full standard deviation above the mean are only 1% and 8% more likely to be open, respectively, for previously open and closed mines. Similarly, firms whose total assets are a full standard deviation above the mean are 11% and 23% more likely to be open, for previously open and closed mines, respectively. As we have already controlled for the mine's particular economics (cost structure), this variable is likely to be capturing the impact on the closing decision of the other sources of profits earned by the firm.[36]

Overall, these results provide some evidence that is consistent with the notion that the decision to close a mine may be determined by the fortunes of the rest of the firm of which it is a part.

Multiple owners and the propensity to close a mine: The decision to close a mine with multiple owners requires that co-owners agree with one another. In other contexts, such as workouts of troubled firms, it has been shown that firms with multiple claimants find it difficult to reach consensus.[37] Therefore, we hypothesize that mines with multiple owners may tend to take longer to reach the decision to close. To test this proposition, we collect information on the ownership stakes of each of the owners of the properties in our sample. In our sample, in 72% of mines are owned by one firm, and 28% are owned by more than one firm. The mean mine is owned by 1.3 firms. We create a variety of variables to capture the ownership structure of the mine and interact each with the prior-state variable. These ownership variables include the following:

- the number of owners of the mine (+);
- the fraction held by the largest owner (-);
- a Herfindahl index of the ownership stakes (-);
- a dummy equal to one if the mine has only one owner (-); and
- a dummy equal to one if the largest owner has 50% or larger share (-).

If mines with multiple owners or less concentrated ownership were slower to close (more likely to stay open) the coefficient on these interaction term would be as noted above.

We added these measures, one at a time, to the specifications given in **Table V**, Panel A. In no case did any of these ownership variables have a statistically significant coefficient, indicating that coordination among operating partners of the decision of whether to close does not exert a measurable influence on the likelihood that an open mine will remain open. Additionally, BRMR specification tests with these additional independent variables cannot reject that the base specification is misspecified.

Stakeholder concerns and the costs of closing a mine: Mine closings have been studied closely by academics who focus on the detrimental impact of permanent and temporary mine closings on local and regional economies.[38] If senior managers take these social welfare externalities into account, mine closings might be less likely when the social costs of closing are large and when the managers are more likely to internalize them. While we do not have information on the social impact of closings, we have data on the location of each of the mines and the corporate headquarters of the owner (or lead owner/operator). For 23% of the mines in our sample, the corporate headquarters is in the same state or province as the mine, but for the remainder the headquarters is located in a different state or province. We create a dummy variable equal to one if the corporate headquarters is located in the same state or province as the mine and interact this variable with the prior state variable. To the extent that managers are more reluctant to close local mines, the coefficient on this variable will be positive (i.e., the mine is more likely to stay open when its corporate officers are in the same community to be affected by the closing).

In no case did either variable representing location of headquarters have a material coefficient when added to the variables in **Table V**. While mining firms may take stakeholder concerns into account when deciding whether to close a mine, we find no evidence that "local" managers act any differently than do out-of-state firms.

VI. Conclusion

In this paper, we study a classic real option: the flexibility that mining firms have to open and shut mines. We document that this flexibility is used frequently, with almost 20% of operational, non-depleted mines closed for stated-economic reasons by late 1997, and many more temporary closed for unstated, but possibly economic, reasons.

Real options theory has long provided a framework to understand the closing decision. We would judge that the theory works reasonably well; The overall pattern of closures is well predicted by real option theory. As predicted, closures are influenced by the price and volatility of gold, firm's operating costs, proxies for closing costs, and the size of reserves. We see strong evidence of hysteresis in the data. This data seems to indicate that managerial flexibility is a material phenomenon in mining—as analysts have suspected for a long time—and that the real options model is a good descriptor of how this flexibility is handled by firms.

While real options models are good stylized representations of plant-level decisions, they often fail to capture aspects of firm-level decision making. We find evidence reminding us that the decision to close a mine may be a firm-level one, rather than a marginal mine-level choice. When a firm has other mines in its portfolio and these other mines have lower operating costs, the current mine is less likely to close. This evidence is consistent with recent research that show that divisions within a firm share a common destiny, and decisions about particular units are influenced by the performance of other parts of the firm.

As we note in our earlier discussion, we cannot tell whether this joint decision-making reflects unobserved joint economies, or whether it suggests a behavioral phenomenon, and it warrants future study. Also, we must be careful not to over-interpret the results of a single industry study. Nevertheless, proponents of real options theory can be vindicated with these results. Real options theory has useful positive and normative implications, and when applied to the "textbook" case, it has much predictive power, suggesting that it is a good descriptor of reality. Further work can help us to understand how firms treat their portfolios of real options.

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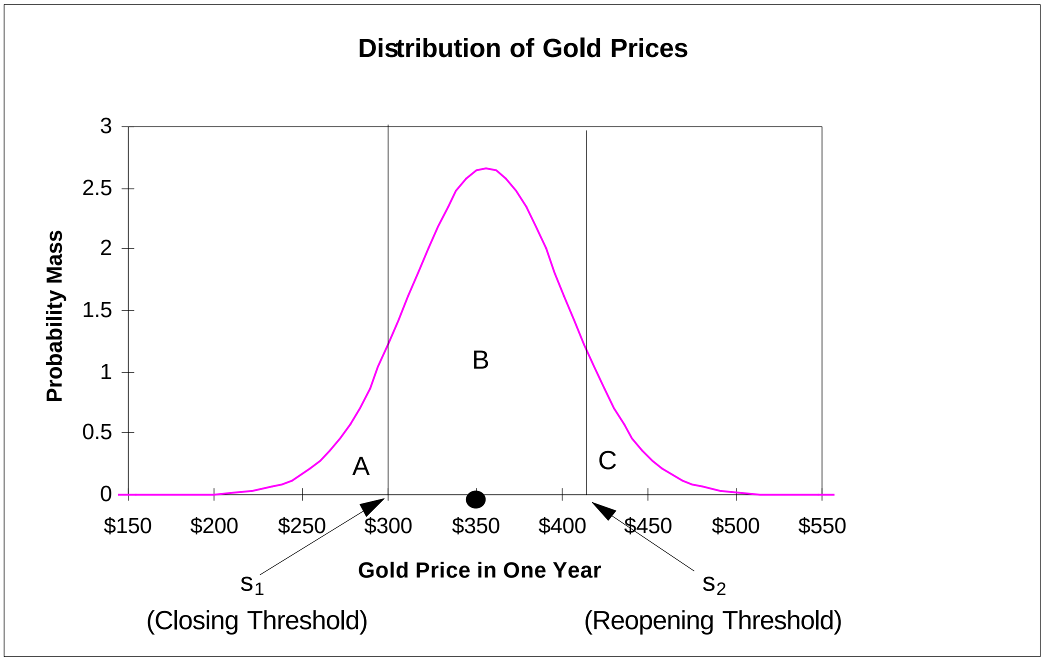


Figure 1
Probability distribution of metals prices and the probability of mine opening or closing. The horizontal axis reflects the gold price in one year and the vertical axis is a plot of the probability distribution of gold price next year. The gold price levels s_1 and s_2 represent the optimal points at which the mine would close (if open) and open (if closed). The dark dot represents the current price. The areas marked A, B, and C are related to the Markov probabilities of the mine being open or closed in the following year:

	Probability of mine being open next year	**Probability of mine being closed next year**
Current state: Open	**B+C**	**A**
Current state: Closed	**C**	**A+B**

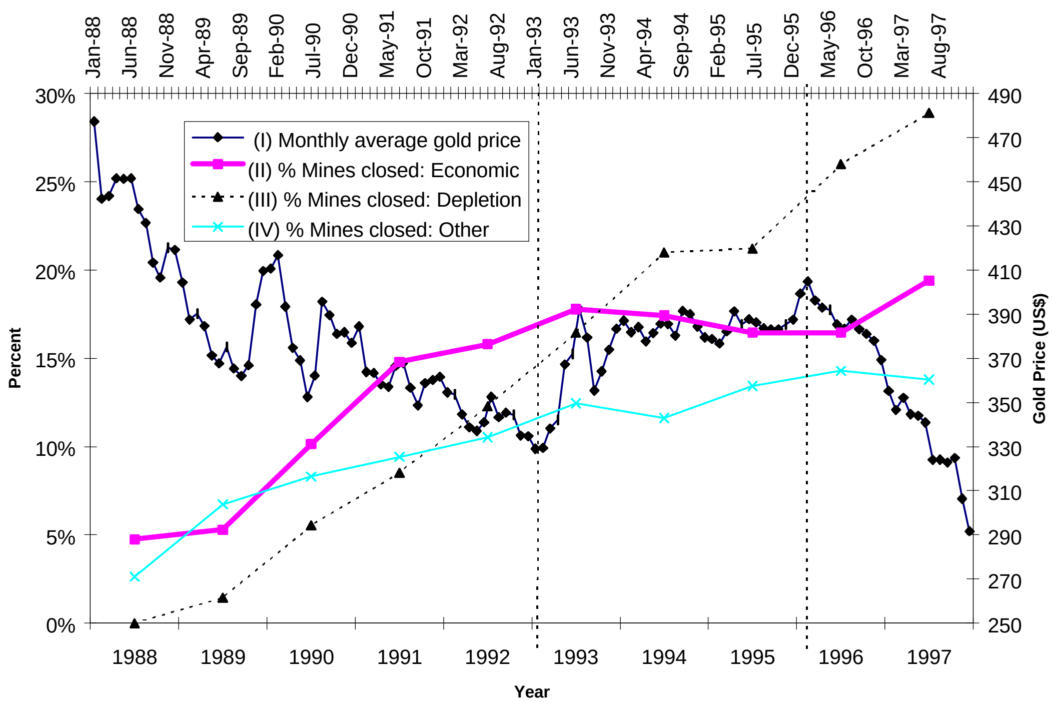
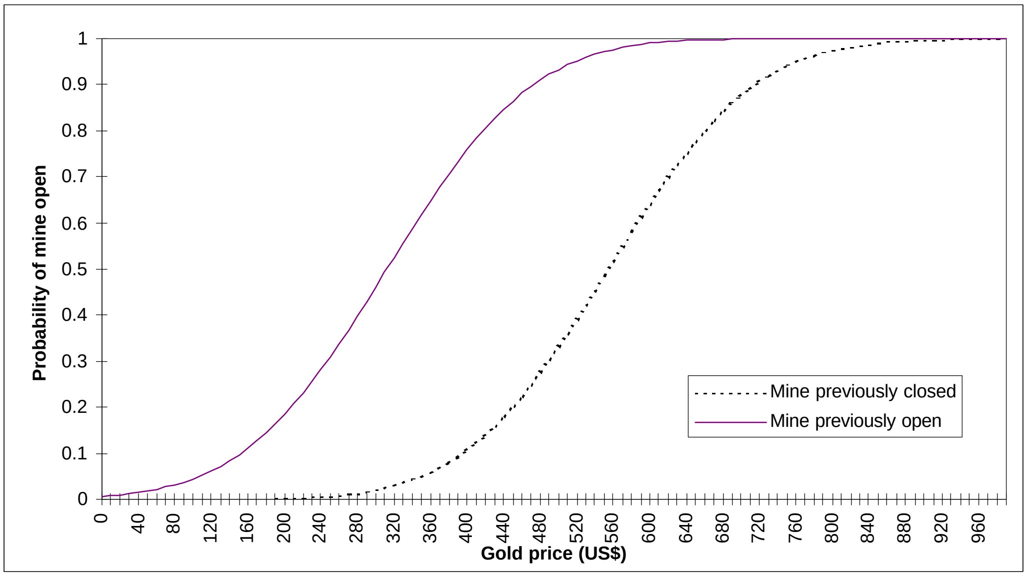


Figure 2
Time series of monthly average gold price, and percentage of closed mines, for the period 1988-1997. Series I shows the monthly average gold price for the period. Series II shows the percentage of mines closed for economic reasons (consisting of the 86 mines classified as having gold price-related closures.) Series III displays the percentage of mines closed out because of depletion (79 mines, reason (2) in **Table II**). Series IV shows the percentage of mines closed for unknown reasons (44 mines, reason (6) in **Table II**). The correlation between series I and II is -0.81, between I and III is -0.62, and between I and IV is -0.76, indicating that all three types of closures are negatively correlated with the price of gold.

PANEL A



PANEL B

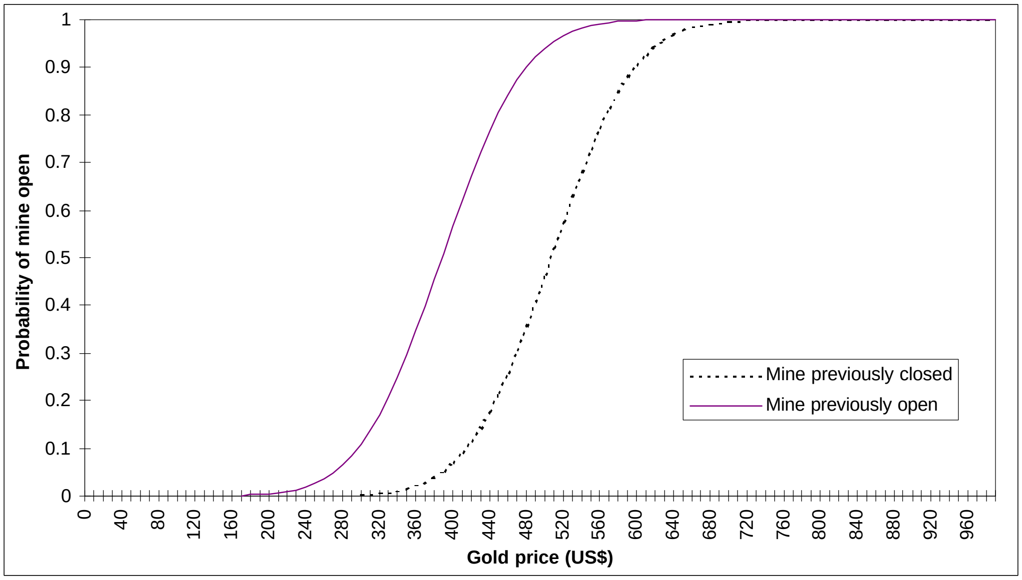


Figure 3: Graphical depiction of probabilities of mine being open from probit analysis The figures show the probability of a mine being open, conditional on the gold price and its state in the prior year. Panel A shows a plot of:

$$f(\text{Au Price}, y_{-1}) = \Phi(g_0 + g_1 \cdot \text{ Au Price} + K + g_3 \cdot y_{-1})$$

for specification C in Panel A of **Table V**, while Panel B shows a plot of the same equation for a specification which includes only mines that closed at some point during the period**.** y_{-1} takes the values 0 or 1 depending on whether the mine was open or closed on the previous year. The gold price is the variable in the *x* axis, and the two plots show the results for y_{-1} equal to 1 (mine open last period) and 0 (mine closed). The constant *K* is the sum of all the other slope coefficients evaluated at their mean values.

Table I
Predictions about the Probability of Mine Status and Data Definitions

The chart below shows the predictions about the variables which should influence the probability that a mine will be open in a given year. Panel A represents predictions from Brennan and Schwartz (1985a) real option model. For example, the probability of a previously open mine remaining open *increases* (+) if the mine was previously open. Similarly, the probability of a mine being open *decreases* (-) is the mine was previously closed. Panel B represent predictions based upon managerial concerns that might affect the decision to close mines, but which are not normally considered in the real options model.

Panel A: Predictions from Real Options Model			
Variable	**Probability of being open, conditional on**		**Variable Definition (source of data)**
	Previously Open	**Previously Closed**	
Prior state	+	-	Open (1) or closed (0) in prior year. (Metallica 2000, Press Reports, Filings)
Gold price	+	+	Average of AM and PM London daily US$ fixing gold prices over prior 12 months. (www.virtual-gold.com)
Volatility of gold price	+	-	Standard deviation (%) of daily gold returns from gold prices plus 3-month lease rate over prior 12 months. (www.virtual-gold.com)
Operating costs	-	-	Predicted marginal costs β (in US$/oz) from estimation of cost function, **Table III**, column E.
Discount rate (nominal)	+	+	Annual average of 10-year T-bond yields. (*Datastream)*
Discount rate (real)	+	+	10-year T-bond yields (*Datastream)* minus expected inflation. (*Federal Reserve Bank of Philadelphia*)
Convenience yield	-	-	Gold lease rate. (www.virtual-gold.com)
Costs of shutting and reopening	+	-	Form of technology dummy variable *T* interacted with prior state variable. (0=open pit or surface mine; 1 = underground mine). (Metallica 2000)
	+	-	Capitalized cost of mine investments in constant 1996 US $, interacted with prior state dummy (Metallica 2000)
Costs of maintaining mine	+	+	Predicted fixed costs α (in US$) from estimation of cost function, **Table III**, column E.
Reserves	+	+	Reserves in oz. (Metallica 2000, Press Reports, Filings)

Panel B: Predictions from Consideration of Managerial Influences on Shutting Decision			
Variable	**Probability of being open, conditional on**		**Variable Definition (source of data)**
	Previously Open	**Previously Closed**	
Portfolio Effects	+	na	Firm may keep mine open longer when other businesses are available to cross-subsidize mine. Variables related to the presence of opportunities for cross-divisional spillover include: • a dummy variable that equals one if the mine is a solo mine (-) • the operating costs of other mines in firm portfolio (-) • the fraction of firm reserves represented by current mine (-) • the firm's overall return on assets in prior year (+) • the size of the firm, measured by its total assets (+) (Metallica 2000, COMPUSTAT)
Coordination	+	na	The requirement to coordinate among parties delays closing decision. Need to coordinate is related to: • the number of owners of the mine (+); • the fraction held by the largest owner (-); • a Herfindahl index of the ownership stakes (-); • a dummy equal to one if the mine has only one owner (-); • a dummy equal to one if the largest owner has 50% or larger share (-) (Metallica 2000, Press Reports, Filings)
Stakeholder Concerns	+	na	Closings affect communities in which mines are located and firms may internalize this externality more when mine located in same state (country) as headquarters of largest owner (Metallica 2000)

Table II
Activities of North American Gold Mines, 1988-1997

This table summarizes the status of developed gold mines in North America from 1988-1997. Developed mines are those which are not classified as exploratory by the *Mining Journal*.

Mine Status		Number of mines
Total number of mines in database		349
Number of mines with insufficient data		64
Number of mines for which data is available		285
Mines that closed at least once during 1988-1997		213[a]
Reason company announced for closure		
(1)	Economics (lower gold prices)	86
(2)	Depletion of reserves	79
(3)	Geological reasons (floods, cave-ins)	11
(4)	Strike or other dispute	3
(5)	Environmental concerns	3
(6)	Reason not given	44
Closed mines that reopened in 1988 – 1997		26
Reason company announced for reopening		
(1)	Economics (higher gold prices)	10
(2)	None given	16

(a) The number of mines in (1)-(6) do not add up to exactly 213 because of double counting. 13 mines closed more than once, for different reasons: 7 because of economic closure and subsequent depletion, 2 for economic closings and other reasons, and 4 due to other reasons followed by depletion.

Table III
Estimation of Cost Functions for North American Gold Mines

Estimation of cost functions for North American gold mines. We estimate the model

$$cq = a_0 + a_1 R + a_2 T + b_0 q + b_1 qT + b_2 D'_R q$$

using OLS over 917 mine-year observations over 1988 to 1997. The coefficients α_0, α_1, and α_2 are the fixed costs, and β_0 , β_1, and β_2 are the marginal costs. *R* is the beginning-year reserves in ounces, *c* is the average (cash) US dollar cost per ounce of gold, and *q* is the annual gold production in ounces. *T* is a technology dummy, equal to 1 if the mine is an underground (UG) mine and 0 if it is an open-pit (OP) mine. Columns A-D show the pooled sample, with and without mine fixed effects, and with the breakdown for the D_R(n) dummies which reflect the reserve quartile. Column E shows the column D specification where costs have been deflated by the Commodity Producer Price Index (CPPI). The final two columns show the cost function broken down by mining technology used. *p*-values are in parenthesis.

	Panel					**Technology**	
	A	**B**	**C**	**D**	**E**	**Under-ground**	**Open Pit**
α_0	5.5E6	4.2E6	3.18E6	1.3E6	1.5E6	5.9E6	5.5E6
	(0.000)	(0.000)	(0.000)	(0.078)	(0.014)	(0.000)	(0.000)
α_1	0.972	2.048	1.310	2.361	2.643	0.329	0.992
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.571)	(0.000)
α_2	5.0E5	-1.9E5	6.5E5	-1.8E5	-1.9E5		
	(0.581)	(0.868)	(0.467)	(0.876)	(0.848)		
β_0	176.07	162.85	211.80	265.46	222.09	150.14	175.69
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
β_1	-34.86	-18.41	-32.59	-16.33	-11.58		
	(0.000)	(0.002)	(0.000)	(0.004)	(0.021)		
Fixed Effects	No	Yes	No	Yes	Yes	No	No
$D_R(2)$			20.62	-30.46	-24.77		
			(0.392)	(0.154)	(0.184)		
$D_R(3)$			-2.23	-82.05	-68.89		
			(0.926)	(0.000)	(0.000)		
$D_R(4)$			-41.74	-106.77	-89.34		
			(0.095)	(0.000)	(0.000)		
N	917	917	917	917	917	353	563
R^2	0.94	0.97	0.94	0.97	0.97	0.82	0.95

Table IV
Mine-Level Characteristics of All Mines and of Mines that Closed

Characteristics of mines that never closed and of mines that closed sometime in the period 1988-1997. Column A shows univariate statistics for all mine-years, while column B shows the same for mines that never closed. The closings correspond to (C) mines closed for economic reasons (86 mines), (D) mines that were depleted (79 mines), and (E) mines closed for unknown reasons (44 mines). α is the estimated mine fixed cost, while β is the estimated mine marginal cost from the specification in **Table III**, column D. The actual number of mine-year observations for each variable is less than or equal the maximum number of observations available. * = means (t-test) or medians (Kruskal-Wallis test) between never closed and closed mines are significantly different to 1%.

	All mines	**Never closed**	**Mines that closed at any point between 1988-1997**		
	A	**B**	**C**	**D**	**E**
			Economic	**Depleted**	**Other**
Maximum observations	2790	1500	860	760	420
Cash costs (US$)					
Mean	270	258	288*	291*	310*
Median	261	248	281*	276*	297*
s.d.	96	95	89	104	126
Reserves (oz)					
Mean	1.02E6	1.35E6	7.53E5*	1.22E6*	3.24E5*
Median	1.77E5	1.59E5	2.88E5*	4.23E4*	9.51E4*
s.d.	3.35E6	4.37E6	1.29E6	2.70E6	6.79E5
Production (oz)					
Mean	66,446	109,883	42,401*	31,294*	10,243*
Median	18,037	53,423	5,162*	22,306*	3,956*
s.d.	164,441	228,565	75,693	30,913	32,680
Au price-cost (US$)					
Mean	109	120	93*	90*	67*
Median	113	125	100*	100*	73*
s.d.	97	96	89	106	131
Predicted fixed cost a (US$)					
Mean	3.66E6	4.46E6	2.98E6*	1.51E6*	1.98E6*
Median	1.64E6	1.61E6	1.87E6*	1.32E6*	1.44E6*
s.d.	8.02E6	1.04E7	3.08E6	6.58E5	1.66E6
Pred. Marginal cost b (US$/oz)					
Mean	203	204	196*	234*	216*
Median	183	219	183*	249*	219*
s.d.	42	45	37	33	37
Capitalized mine cost (M US$)					
Mean	36	34	42*	20*	29
Median	18	22	21	10*	7*
s.d.	53	40	56	24	80
Technology					
% Underground	42%	43%	42%	35%	38%
% Open pit	58%	57%	58%	65%	62%

Table V
Probit Analysis of the Likelihood of a Mine Being Open, Conditional on Market Conditions and Firm Characteristics

Probit analysis of the likelihood of a mine being open for different specifications. We compute the model

$$\text{Prob}(y=1)=\Phi(b'\mathbf{x}+y_{-1})$$

where *y* is a dummy variable that equals one if the mine if open in a given year, Φ(.) is the cumulative normal distribution, $\boldsymbol{\beta}'\mathbf{x}$ are the regressors **(**described in **Table I**), postulated to affect the probability of opening and closing, and y_{-1} is a dummy variable indicating if the mine was open in the *previous* year. In column F all dollar values are deflated by the commodity producer price index (CPPI) and real interest rates are used. The real rates were estimated by subtracting the expected inflation from the 10-year T-bond rates. The first number in each cell is the regression coefficient. The second number is the slope of the marginal probabilities for each regressor x_i, given by

$$\frac{\partial \text{Prob}(y=1)}{\partial x_i}=f(b'\bar{\mathbf{x}})b_i$$

where $b'\bar{\mathbf{x}}$ are the sum of the coefficients times the mean value of the independent variable, and f is the standard normal density function. The numbers in parentheses are the *p*-values for the significance of the coefficient. The pseudo-R^2 is calculated as in Greene (1997), p. 891. Panel A shows the results for a simple probit specification, while Panel B shows the same for a random effects specification to correct for contemporaneous correlation, as suggested by Pendergast *et al.* (1996).

PANEL A

	Mean Value	Sign	A	B	C	D	E	F
Intercept			-2.612	-3.473	-1.808	-3.818	-1.607	-3.873
			(0.000)	(0.000)	(0.079)	(0.000)	(0.166)	(0.000)
Gold Price (US$)		+	0.004	0.006	0.006	0.006	0.001	0.010
Nominal:	367.16		0.0016	0.0024	0.0023	0.0022	0.0004	0.0039
Deflated:	337.09		(0.021)	(0.011)	(0.010)	(0.012)	(0.888)	(0.000)
Gold volatility interacted	0.12	+		1.949	2.027	2.002	1.149	3.108
with open last year				0.777	0.793	0.745	0.416	0.830
dummy				(0.047)	(0.054)	(0.052)	(0.364)	(0.006)
Gold volatility interacted	0.12	-		-0.518	-0.975	-0.756	-3.008	-1.389
with closed last year				-0.206	-0.382	-0.281	-0.728	-0.547
dummy				(0.575)	(0.335)	(0.446)	(0.016)	(0.230)
Fixed Costs α (US$)		+			1.09E-7		8.12E-8	7.28E-8
Nominal:	3.66E6				4.27E-8		2.94E-8	2.87E-8
Deflated:	3.53E6				(0.001)		(0.052)	(0.051)
Marginal Cost β (US$/oz)		-			-0.009		0.009	-0.011
Nominal:	203				-0.004		0.003	-0.004
Deflated:	171				(0.000)		(0.000)	(0.000)
Reserves (oz)	1.02E6	+				7.36E-7		
						2.74E-7		
						(0.000)		
10 Year T-Bond rate		+					0.324	0.192
Nominal:	7.29%						0.117	0.076
Real:	3.64%						(0.000)	(0.057)
Gold lease rate	1.30%	-					0.030	0.009
							0.011	0.004
							(0.782)	(0.940)
Open last year dummy y_{-1}	0.46	+	2.199	2.488	2.399	2.363	2.235	2.281
			0.870	0.991	0.939	0.880	0.810	0.899
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
N			2056	2056	2056	2056	2056	2056
Pseudo R^2			0.42	0.43	0.50	0.48	0.58	0.58

PANEL B

	Mean Value	Sign	A	B	C	D	E	F
Intercept			-2.427	-3.218	-1.201	-2.726	-8.127	-4.255
			(0.000)	(0.000)	(0.079)	(0.000)	(0.000)	(0.000)
Gold Price (US$)		+	0.004	0.006	0.006	0.006	0.013	0.006
Nominal:	367.16		0.0016	0.0024	0.0025	0.0022	0.0026	0.0018
Deflated:	337.09		(0.033)	(0.043)	(0.021)	(0.012)	(0.999)	(0.000)
Gold volatility interacted with open last year dummy	0.12	+		2.001	1.032	2.002	1.122	2.255
				0.743	0.641	0.745	0.331	0.791
				(0.032)	(0.054)	(0.052)	(0.677)	(0.009)
Gold volatility interacted with closed last year dummy	0.12	-		-0.342	-0.419	-0.456	-0.624	-0.274
				-0.321	-0.403	-0.481	-0.098	-0.099
				(0.746)	(0.614)	(0.636)	(0.038)	(0.644)
Fixed Costs α (US$)		+			1.02E-7		2.43E-08	3.25E-08
Nominal:	3.66E6				3.22E-8		4.31E-09	1.14E-08
Deflated:	3.53E6				(0.001)		(0.052)	(0.009)
Marginal Cost β (US$/oz)		-			-0.009		-0.004	-0.015
Nominal:	203				-0.004		-0.002	-0.005
Deflated:	171				(0.000)		(0.000)	(0.000)
Reserves (oz)	1.02E6	+				6.36E-7		
						1.74E-7		
						(0.000)		
10 Year T-Bond rate		+					0.154	0.078
Nominal:	7.29%						0.036	0.027
Real:	3.64%						(0.000)	(0.050)
Gold lease rate	1.30%	-					0.482	0.025
							0.129	0.009
							(0.827)	(0.999)
Open last year dummy y_{-1}	0.46	+	2.325	2.214	2.399	2.010	2.025	1.997
			0.902	0.735	0.939	0.721	0.542	0.701
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
N			2056	2056	2056	2056	2056	2056
Pseudo R^2			0.37	0.37	0.42	0.46	0.52	0.52

Table VI
Characteristics of Firms Owning All Mines and Mines that Closed

Characteristics of firms that owned mines in the period 1988-1997. Column A shows univariate statistics for all firms, while column B shows the same for firms that owned mines that never closed. The other columns report characteristics of firms whose mines closed for for economic reasons (86 mines) in column C, of mines that were depleted (79 mines) in column D, and of mines closed for unknown reasons (44 mines) in column E. The actual number of observations for each variable is less than or equal the maximum number of observations available. A firm-year is considered to "own" a mine if it has an interest on a given year. * = means (t-test) or medians (Kruskal-Wallis test) between never closed and closed mines are significantly different to 1%.

	All mines	Never closed	Mines that closed at any point between 1988-1997		
	A	**B**	**C**	**D**	**E**
Maximum number of observations			**Economic**	**Depleted**	**Other**
Mine-years	2850	1540	870	790	440
Firm-years	2494	1278	824	631	392
Accounting data firm-years	1859	1054	564	505	241
Mine portfolio—Mines per firm:					
Number of mines owned per firm:					
Mean	3.03	3.49	2.87*	3.24	1.87*
Median	2.00	3.00	2.00*	3.00	1.00*
s.d.	2.33	2.51	2.16	2.27	1.44
Fraction of mine-years owned by Single mine firms	0.42	0.37	0.43	0.43	0.59*
Firm-year total assets (M US$)					
Mean	999.71	1301.70	721.61*	885.00*	329.86*
Median	283.31	493.70	191.35*	246.05*	19.66*
Firm-year ROA					
Mean	-0.08	-0.03	-0.13*	-0.07*	-0.21*
Median	0.01	0.02	-0.01*	0.01*	-0.11*
Year-End MV of Equity (M US$)					
Mean	1223.45	1664.29	872.65*	1130.68*	348.66*
Median	340.93	697.44	321.11*	223.31*	26.88*
Need to coordinate—Firms per mine:					
Number of owners per mine-year					
Mean	1.32	1.33	1.27*	1.25*	1.35
Median	1.00	1.00	1.00	1.00	1.00
s.d.	0.54	0.56	0.51	0.50	0.56
Fraction of mine-years owned by one firm	0.72	0.71	0.76	0.78*	0.70
Stakeholder Concerns— *Share of mines located in firm with headquarters in same state/province*	0.23	0.23	0.17*	0.22	0.32*

Table VII
Probit Analysis of the Likelihood of a Mine Being Open, Conditional on Market Conditions, Mine Characteristics, and Firm's Portfolio of Mines

Probit analysis of the likelihood of a mine being open for different specifications. We compute the model

$$\text{Prob}(y=1)=\Phi(b'\mathbf{x}+y_{-1})$$

where y is a dummy variable that equals one if the mine if open in a given year, $\Phi(.)$ is the cumulative normal distribution, $\boldsymbol{\beta}'\mathbf{x}$ are the regressors **(**described in **Table I**), postulated to affect the probability of opening and closing, and y_{-1} is a dummy variable indicating if the mine was open in the *previous* year. The data is for all 285 mines in the sample. **Panel A** analyzes mine ownership variables, while **Panel B** shows results for firm profitability and size variables. The first number in each cell is the regression coefficient. The second number is the slope of the marginal probabilities for each regressor x_I, given by

$$\frac{\partial \text{Prob}(y=1)}{\partial x_i}=f(b'\overline{\mathbf{x}})b_i$$

where $b'\overline{\mathbf{x}}$ are the sum of the coefficients times the mean value of the independent variable, and f is the standard normal density function. The numbers in parentheses are the p-values for the significance of the coefficient. The pseudo-R^2 is calculated as in Greene (1997), p. 891. The specifications match those with the same column label (e.g., A) from **Table V.**

PANEL A

	Mean Value	Sign	A	B	C	D
Intercept			-2.542 (0.000)	-3.311 (0.001)	-2.016 (0.059)	-3.578 (0.000)
Gold price (US$)	367.16	+	0.004 0.0016 (0.027)	0.006 0.0024 (0.020)	0.006 0.0024 (0.012)	0.006 0.0023 (0.021)
Gold volatility interacted with open last year dummy *y_{-1}*	0.12	+		1.868 0.7452 (0.070)	2.046 0.8144 (0.059)	1.909 0.7335 (0.074)
Gold volatility interacted with closed last year dummy	0.12	-		-0.761 -0.3036 (0.446)	-1.283 -0.5107 (0.226)	-1.150 -0.4418 (0.271)
Fixed costs α (US$)	3.72E6	+			9.52E-8 3.79E-8 (0.005)	
Marginal cost β (US$/oz)	212.41	-			-0.008 -0.0032 (0.000)	
Reserves (oz)	1.03E6	+				5.98E-7 2.30E-7 (0.000)
Average marginal cost of "other mines" times open last year dummy *y_{-1}*	78.22	-	-0.005 -0.0020 (0.002)	-0.005 -0.0020 (0.002)	-0.002 -0.0008 (0.084)	-0.003 -0.0012 (0.062)
Fraction of reserves by current mine times open last year dummy *y_{-1}*	0.27	+	1.161 0.4528 (0.000)	1.149 0.4584 (0.000)	0.432 0.1720 (0.040)	0.649 0.2494 (0.002)
Solo-mine dummy times open last year dummy *y_{-1}*	0.14	-	-1.871 -0.7298 (0.000)	-1.864 -0.7436 (0.000)	-1.043 -0.4152 (0.000)	-1.197 -0.4599 (0.000)
Open last year dummy *y_{-1}*	0.41	+	2.928 0.752 (0.000)	3.239 0.893 (0.000)	2.891 0.753 (0.000)	2.852 0.712 (0.000)
Random effects			No	No	No	No
N			1906	1906	1906	1906
Pseudo *R^2*			0.44	0.44	0.49	0.48

PANEL B

	Mean Value	Sign	A	B	C	D
Intercept			-2.642 (0.001)	-4.360 (0.000)	-2.614 (0.110)	-4.865 (0.000)
Gold price (US$)	367.16	+	0.005 0.002 (0.041)	0.008 0.003 (0.003)	0.009 0.003 (0.002)	0.009 0.003 (0.008)
Gold volatility interacted with open last year dummy *y_{-1}*	0.12	+		3.772 0.707 (0.002)	4.323 0.869 (0.001)	4.196 0.688 (0.001)
Gold volatility interacted with closed last year dummy	0.12	-		-0.352 -0.140 (0.761)	-0.515 -0.193 (0.682)	-0.432 -0.135 (0.727)
Fixed costs α (US$)	3.91E6	+			8.46E-8 3.16E-8 (0.038)	
Marginal cost β (US$/oz)	210.64	-			-0.010 -0.004 (0.000)	
Reserves (oz)	1.11E6	+				7.56E-7 2.37E-7 (0.000)
Profitability: Lagged ROA times open last year dummy *y_{-1}*	-0.08	+	0.635 0.253 (0.000)	0.625 0.249 (0.000)	0.462 0.173 (0.003)	0.471 0.148 (0.003)
Firm Size: Lagged book value of assets (Mil US$) times open last year dummy *y_{-1}*	999.71	+	9.0E-5 3.6E-5 (0.031)	8.9E-5 3.6E-5 (0.036)	4.1E-5 1.5E-5 (0.352)	3.3E-5 1.0E-5 (0.444)
Open last year dummy *y_{-1}*	0.38	+	2.143 0.854 (0.000)	2.598 0.957 (0.000)	2.590 0.968 (0.000)	2.553 0.800 (0.000)
Random effects			No	No	No	No
N			1532	1532	1532	1532
Pseudo R^2			0.45	0.43	0.50	0.48

Notes

[1] Other mining options include the option to develop a property or wait, the option to change the rate of production, and the option to adjust the grade of ore mined. For examples of these other options, see Mardones (1993) or Smit (1997).
[2] Other examinations of the exit (and entry) decision can be found in Caton and Linn's (1998) study of exit in the chemical products industry, Schary's (1991) work on exit in the cotton textile industry, and Bernanke's (1983) discussion of entry.
[3] Slade's (2000) research of the value of managerial flexibility at 21 Canadian copper mines is a contemporaneous and related study to ours.
[4] They also model the development, abandonment, and operating level option, which we do not study in this paper.
[5] See, for example, Dixit (1989), or Brennan and Schwartz's (1985a) characterization of Pindyck (1980). The model in Dixit (1989) is easily extended to include risk aversion (see Dixit (1989), p. 636-637). The resulting differential equation is observationally-equivalent to that developed by Brennan and Schwartz (1985a).
[6] A decision-analysis approach requires the decision maker to specify objective probabilities and a utility function to arrive at a private valuation. For a comparison of the differences between real options and decision analysis, see Teisberg (1995) or Kasanen and Trigeorgis (1995).
[7]If the distribution of metals prices used was the objective or true distribution, then these probabilities would reflect the objective likelihood of the mine being open or closed. However, if we were to use a risk-neutral distribution of future metals prices, then the probabilities would reflect the risk-neutral likelihood of the mine being open or closed. The comparative statics calculations are available from the authors.
[8] Brennan and Schwartz (1985a) assume that gold price returns follow a Geometric Brownian Motion with constant volatility. If gold prices were assumed mean reverting, or if volatility itself was stochastic, this might impact the open or closing decision. Bessembinder, Coughenour, Seguin, and Smoller (1995) show that, although gold prices are mean-reverting, the degree of mean reversion is small enough that a random walk is a good approximation. Akgiray, Booth, Hatem, and Mustafa (1991) provide empirical evidence that gold return volatility follows a GARCH(1,1) process. However, the effect of the conditional heteroskedasticity of previous period volatility on current volatility is economically small, from which we infer that a constant volatility approximation is adequate for our empirical tests.
[9] Reserve data is not generally available each year. We estimated reserve data for the missing years by subtracting known gold production in those years from the previously reported reserves.
[10] These can be thought of as "economic" closings in that these events lead to a very high or infinite costs of production. We recognize that there are other investment and exit decisions which arise from strategic behavior of economic actors, whereby firms signal to one another using visible decisions. See Ghemawat and Nalebuff (1985, 1990) for a discussion. In the commodity gold industry, these concerns seem less relevant than in less than perfectly competitive markets.
[11] The *Mining Journal* CD-ROM contains all back issues of *Mining Journal, Mining Database,* and *Mining Annual Review* for 1981-1996 in electronically-searchable form.
[12] In this search, we examined all news stories using the mine name and company name as the search terms.
[13] We are able to identify a precise date for the closing announcement for 27 of the mines that closed for economic reasons. We conducted an event study of these closing announcements, using standard methodology, using a 250 day event window. In the two day window surrounding the mine closing announcements, the firms experienced an abnormal return of -0.6%, which was statistically insignificant from zero. This might suggest that these closings were predicted by investors or that the mines closed only made a modest contribution to firm value. Given the paucity of data, it is probably wise not to over-interpret this event study finding.
[14] We thank Jessica Cross for her cooperation in making this data available. This information can be accessed at http://www.virtual-gold.com.
[15] The Survey of Professional Forecasters was formerly known as the ASA-NBER Survey. There is evidence (e.g. see Hafer and Hein (1985), Graham (1995), and Croushore (1998)) that, from the mid-

1980's until the present, survey forecasts are as good (and sometimes better) predictors of inflation and GNP as are time-series (for example, St-Amant (1996)), or interest rate models (such as Fama and Gibbons (1984)).

[16] Cumulative production also seems related to costs. We proxy for cumulative production by using reserves, because we do not have production information from prior to 1988 needed to calculate cumulative production.

[17] The functional form of the cost function regression resulted from of our study of the literature in mineral economics (e.g. Campbell and Wrean (1985)) and from discussions with mineral economists. Nevertheless, because of the linearity and the use of reserve quartiles, specification error might be present. To test for specification error, we carried out Durbin-Watson and Breusch-Pagan tests for autocorrelation (non-linearity) in the residuals. The statistics indicate that the first-order autocorrelation was at most 10%, indicating that the model is not misspecified. Similarly, the use of a Box-Cox transformation followed by ML estimation provides evidence that a linear model is appropriate. A Regression Specification Error Test (RESET) shows that coefficients on production and reserves squared are statistically significant. However, they are economically insignificant (about four orders of magnitude smaller than the linear terms). Thus, the linear approximation is justified.

[18] For example, in producing gold, waste products collect in a tailings pond. This normally wet pond might dry up after a long period of being shut, and toxic waste products would blow around. Maintenance might require that the pond be continually kept wet through pumping water into it. We are using fixed costs to capture this aspect of a mine's cost structure. Fixed costs themselves would not affect any temporary closing decision, as they could not be avoided.

[19] Ideally, one would estimate cost functions for each mines separately, rather than in a panel However, we have a maximum of 10 observations of costs per mine, if they were open the full decade we study. As a test of whether the panel estimation provided similar estimates as separate estimation, for 14 of the mines in our sample with complete date over the entire period, we were able to estimate the simple specification: $cq = a_0 + a_1 R + b_0 q$ with a 5% significant *F*-statistic, and with all coefficients significant to 5% or better. The cost estimates for these mines and the panel estimates were similar, which suggests that using the panel predicted costs is acceptable.

[20] If a mine is to be shut for a short period, one can just "shut out the lights" and force workers to take accrued leave; but for longer periods, closing costs may include reconfiguring equipment and offering workers some sort of severance package.

[21]Mines that closed without reporting a reason follow a pattern somewhat similar to those of mines closed for economic reasons, but fail to demonstrate as strong hysteretic behavior. Furthermore, the "unknown" closures did not respond to the price drops in 1996-1997 as much as the "economic" closures.

[22] An important question is whether the use of the linear and Gaussian probit latent variable model is justified here. In the Brennan and Schwartz (1985) model, the random variable is the gold price return, which is normally distributed. Although the model is non-linear, we carried out Monte-Carlo simulations of the model under the assumption that the independent variables are all random variables (The probability distribution function for each independent variable was constructed by fitting the first four sample moments of the independent variables to an assumed distribution function using the method of moments (Greene (1997), Chap. 4)). The opening and closing costs are not known, so we carried out simulations for a range of opening and closing costs from 0 to $100 million. In general, we cannot reject that the resulting distribution of opening and closing thresholds (the latent variable) are not Normally distributed. To test for linearity, we applied the Box-Cox transformation to the data, and compared the estimated value of the non-linear parameter λ to $\lambda = 1$ using the standard likelihood ratio test. The test statistic, which is $\chi^2[1]$-distributed equals 3.22. For the $\chi^2[1]$ distribution, the critical value is 3.84, thus the assumption of linearity cannot be rejected. Given these results, we feel justified, at least for this data set, in using a linear and Gaussian probit specification, with standard maximum likelihood estimation, to test the real options models.

[23] We cannot run the regressions with average (cash) costs as an independent variable because these costs are not reported for closed mines.

[24] Because we are using point estimates for fixed and marginal costs obtained from a linear regression (**Table III**) as independent variables in a probit regression (**Table V**), the coefficient estimates from **Table III** are measured with error, leading to a potential error-in-variables problem. If this measurement error is uncorrelated or positively correlated to the true parameter, then the coefficients for the fixed and marginal costs will be biased towards zero (and thus towards lower statistical significance) in the probit regression. We tested if this description of errors was found in the data by separating the sample into small and large mines, and calculating their cost parameters separately. We compared these separate cost parameters with the cost parameters of the single regression, and calculated the error between the split and joint regression. The errors for the small firms were larger (and statistically significantly different) than the errors for the large firms. Given that smaller mines have higher unit costs, higher unit costs are probably measured with more error than small unit costs. Thus measurement error is positively correlated with the cost variables, and thus it appears that the true probit coefficients would be even larger than those we report.

[25] In theory, the real options model and decision-theoretic models with risk aversion (e.g. Dixit 1989) are differentiated by the rate at which the project's cash flows are discounted. In real options models, there exists a hedging portfolio, and thus the relevant discount rate is the *riskless* rate. In the decision theoretic models an extra risk premium for systematic risk is included, and thus the discount rate is the *risky* rate appropriate for the project. The comparative statics from both models, however, are identical, and we are unable to empirically distinguish between these two classes of models.

[26] These are calculated from the specification in column D, where the base probabilities are 23.7% and 95.0% for previously closed and open mines.

[27] We thank David Laughton for bringing this point to our attention.

[28] Firms may have incentives to label mines as "closed" rather than abandoned, because in the US, this latter designation apparently triggers the requirement that the firm environmentally "reclaim" the property.

[29] Henriksson and Merton (1981) develop a non-parametric test for evaluating a market timer's forecast of next-period security returns. The forecaster makes a prediction on whether the market will be "up" or "down" in the next period. Under the null hypothesis, the probability distribution for the number of correct forecasts given the actual outcomes (either "up" or "down") has the form of a hypergeometric distribution, and does not depend on the underlying outcomes being drawn from a particular distribution. The prediction problem analyzed here is of the same type.

[30] As an example, see Hannan, Burton and Baron (1996).

[31] We only have information on gold mining properties; these solo-mine firms may have other non-gold mines.

[32] This argument would be related to Jensen's (1993) contention for why diversified firms may be reluctant to exit from poorly performing businesses.

[33] An alternative to this "missing data" approach is to test only the subset of mines that are part of a mine portfolio. We also carried out this test; the results (not reported) are similar to those presented in **Table VII,** Panel A**.**

[34] This calculation incorporates the effects of both the solo-mine dummy and the fraction of reserves term. The multi-mine firm has a solo-firm dummy equal to zero and fraction of reserves equal to the mean for the sample. The solo-mine firm has a solo-firm dummy equal to one and fraction of reserves equal to 1.0.

[35] As a check, we also ran a restricted *F*-test on the linear probability model of our specification, with similar results.

[36] However, neither return on book equity nor return on sales have a consistent positive relationship with the likelihood of a mine being open, which may suggest that this result is not robust.

[37] This is related to the finding by Gilson, John and Lang (1990) that troubled firms with more claimants (lenders) are less likely to be able to negotiate an out-of-court restructuring voluntarily.

[38] For example, see the volume by Neil, Tykkylainen, and Bradbury (1992) that studies the consequences of 16 mine closings in different countries.