Examining Risk in Mineral Exploration

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Examining Risk in Mineral Exploration

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Successful mineral exploration strategy requires identification of some of the risk sources and considering them in the decision-making process so that controllable risk can be reduced. Risk is defined as chance of failure or loss. Exploration is an economic activity involving risk and uncertainty, so risk also must be defined in an economic context. Risk reduction can be addressed in three fundamental ways: (1) increasing the number of examinations; (2) increasing success probabilities; and (3) changing success probabilities per test by learning. These provide the framework for examining exploration risk. First, the number of prospects examined is increased, such as by joint venturing, thereby reducing chance of *gambler's ruin*. Second, success probability is increased by exploring for deposit types more likely to be economic, such as those with a high proportion of world-class deposits. For example, in looking for 100+ ton (>3 million oz) Au deposits, porphyry Cu–Au, or epithermal quartz alunite Au types require examining fewer deposits than Comstock epithermal vein and most other deposit types. For porphyry copper exploration, a strong positive relationship between area of sulfide minerals and deposits' contained Cu can be used to reduce exploration risk by only examining large sulfide systems. In some situations, success probabilities can be increased by examining certain geologic environments. Only 8% of kuroko massive sulfide deposits are world class, but success chances can be increased to about 15% by looking in settings containing sediments and rhyolitic rocks. It is possible to reduce risk of loss during mining by sequentially developing and expanding a mine—thus reducing capital exposed at early stages and reducing present value of risked capital. Because this strategy is easier to apply in some deposit types than in others, the strategy can affect deposit types sought. Third, risk is reduced by using prior information and by changing the independence of trials assumption, that is, by learning. Bayes' formula is used to change the probability of existence of the deposit sought on the basis of successive exploration stages. Perhaps the most important way to reduce exploration risk is to employ personnel with the appropriate experience and yet who are learning.

KEY WORDS: Risk; mineral exploration; decision-making; mineral economics; mineral resources; risk assessment; Bayes.

INTRODUCTION

Exploration can be characterized as a multistage search process in which only the last stage, drilling, is usually definitive. At each stage, an attempt is made to reduce the area to which the next, typically more expensive, stage of search is applied. Each stage may be viewed as an attempt to discriminate between areas that contain valuable deposits and areas that do not. Because deposit detection is probabilistic, at each stage, classification errors of both types (that is rejecting valuable deposits and accepting nonvaluable prospects) and their associated costs must be balanced against the possible gains of discovering an economic deposit. A successful exploration strategy requires identification of the sources of risk and considering them in the decision-making process so that controlla-

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ble risk can be reduced. Risk is defined as the chance of failure or loss. It can be represented by a probability, a decision table, or a plot of probability vs. outcome. Exploration is an economic activity, so the definition of failure also must be economic; that is, a technical success of locating a mineral deposit must be considered a failure if the deposit is not economic to mine at the time of discovery.

It is not uncommon to see recommendations that exploration firms should accept all projects with positive expected monetary values; namely, projects that have a positive economic value after being multiplied by the probability of deposit discovery and subtraction of exploration costs. Clearly this strategy would be unwise for a firm with limited resources if the chance of failure were significant. Both expected monetary values and the probabilities of various outcomes, such as economic failure, should be considered in the decision-making process. Because economic return, when measured by net present value, is related closely to the size of mineral deposits and deposit sizes can be represented by highly skewed frequency distributions, achieving expected monetary or higher values tends to be a low-probability outcome. This and the typical rarity of mineral deposits are the fundamental reasons for the high risk in mineral exploration.

Exploration risks can be reduced using strategies based on geology, statistics, and economics. Among the possible sources of risk in exploration are: variation of deposit sizes and grades among deposit types, variation in deposit sizes and grades within types resulting from local or regional differences in geologic settings, variation in economic returns by type, price changes, and discovery chances, given existence of deposits. In this paper we focus primarily on strategies based on geology and statistics that can be used in the early stages of exploration. Risk reduction related to ore-reserve estimation has been addressed by others (Mackenzie, 1994).

First, we present the basic ideas of risk as they apply to exploration—a basic equation provides the framework for addressing risk in this paper. The most direct way to reduce risk by increasing the number of prospects examined is considered next. Another way to reduce risk is to lower the probability of failure by directing exploration to deposit types that have a higher probability of being located. Risk reduction then is considered through the use of targeted geologic settings. Various methods also are available to reduce economic risk in the exploration, development, and mining phases (Moore and Drew, 1979). Finally, we discuss risk reduction by using prior information and by changing the assumption of independence in a sequence of exploration examinations, that is, by learning. Although it is implicitly assumed that multiple decisions are made in an exploration program, some of the tools presented here can be used in small companies for single-event decisions.

BASICS OF RISK

In its most elemental form, risk can be considered the probability of failure. For example, if we predict heads when a coin is flipped, the risk of failure is that tails might be the result. In the long term, under these conditions, we expect that our probability of losing on any single coin toss will be 0.5. We also can ask what is the probability of two losses (tails) in a row. If the results of one coin toss have no effect on the next coin toss, the events are independent, and the probability of two losses is 0.25 (that is, 0.5×0.5). We also can calculate the probability of at least one success (head) as one minus the probability of both coin tosses being tails ($1.0 - 0.5 \times 0.5$), or 0.75. The same rules apply if there are three coin tosses; the probability of at least one success is $1.0 - 0.5 \times 0.5 \times 0.5$, or 0.875. Generalizing this: the probability of at least one success can be estimated as 1.0 minus the probability of failure multiplied by itself as many times as there are trials:

$$P_{\text{success}} = 1 - (p_{\text{failure}})^n \qquad (1)$$

where P_{failure} is the probability of failure in one trial and n is the number of trials. These simple ideas form the foundation for examining exploration risk and reducing it to acceptable levels. In the following sections, each part of this equation is examined.

RISK REDUCTION BY INCREASING NUMBER OF TRIALS

Slichter (1960) said that the only way to avoid *gambler's ruin* in mineral exploration [Eq. (1)] was to have enough capital to have many trials, that is have a large n (see Fig. 1). Thus, the classic way to reduce risk in exploration is to increase the number of prospects examined (n). Consideration of this was central to the successful exploration and discovery of the Middle Tennessee zinc deposit at Elmwood (Callahan, 1977). The number of prospects which must be examined for

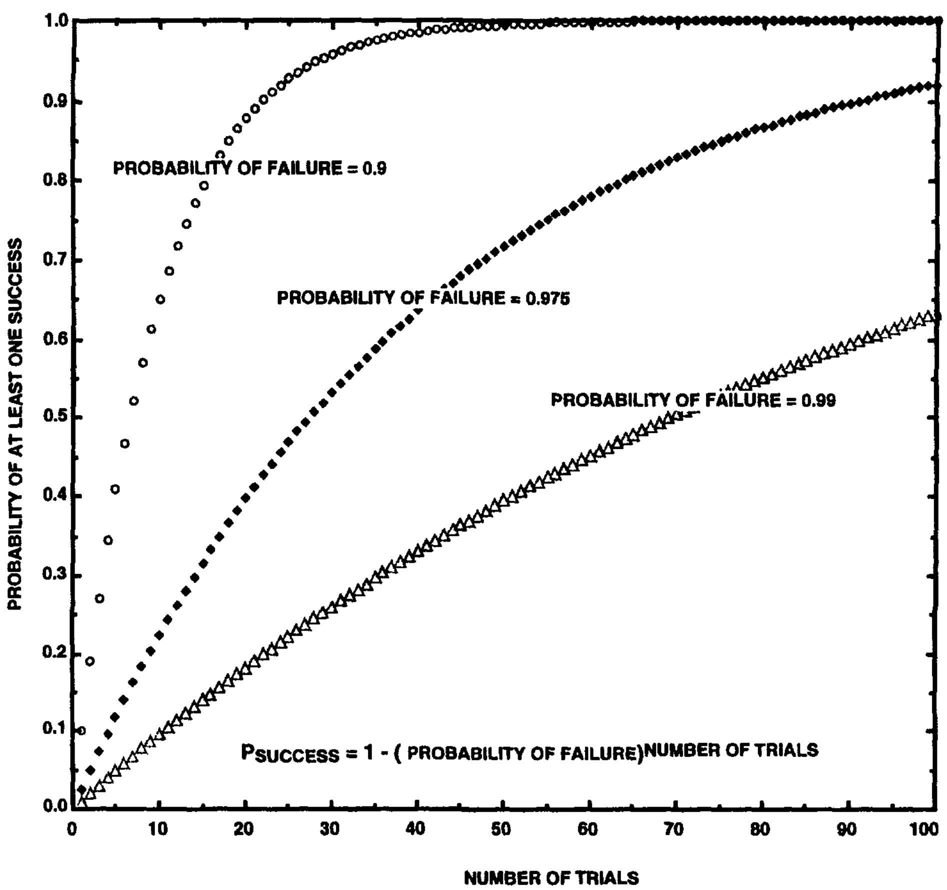

Figure 1. Probability of at least one success plotted against number of trials for different probabilities of failure for single trials.

a fixed probability of at least one success ($P_{success}$), can be calculated as:

$$n = \log(1 - P_{success})/\log(p_{failure}) \qquad (2)$$

Risk reduction by increasing the number of prospects examined, whether through submittals from smaller companies or from internal prospect generation, should give a significant advantage to large firms because only they would have the financial resources to pursue such a policy. Joint venturing, where exploration expenses, responsibilities, and benefits are shared among companies, is the most usual way to take advantage of this method of risk reduction, such as at Yanacocha, Peru, Ladolam, Papua New Guinea, and Lone Tree, Nevada (Sillitoe, 1995). Along with the reduced risk of economic failure comes a reduced financial return in joint ventures. Even with large resources for exploration, at some point, expenses of exploration can exceed the value of the target; thus, there are limits to this method. However, there are other ways to reduce exploration risk that have some advantages over this brute force method.

RISK REDUCTION BY CHANGING PROBABILITY OF FAILURE

It is clear from Figure 1, that if the probability of failure in a single trial can be reduced, then the probability of at least one success increases dramatically for a given number of trails. Looking for targets that are easier to find can reduce the probability of failure per trial, where a trial refers to the examination of a prospect or a deposit that might be economic.

Risk Reduction Among Deposit Types

In mineral exploration, easier to look for more widely occurring and typically smaller deposits, or in places previously unexplored. The problem is that at some point, the deposits are so small that they are not economic to mine. Small deposits and occurrences are so numerous that they quickly would consume available exploration money if they were the target. The importance of target size on exploration risk can be shown by the following equation in which the expected amount of metal is estimated from a population of deposits:

$$E(\text{metal}) = E(n) \cdot 10^{(\hat{u}\text{tons}+\text{vartons}/2+\hat{u}\text{grade}+\text{vargrade}/2)} \quad (3)$$

where E(metal) is the expected amount of metal, $E(n)$ is the expected number of deposits, ûtons is the mean of logged tonnage, vartons is the variance of tonnage, ûgrade is the mean of logged grade, and vargrade is the variance of grade. An important measure of economic success, net present value, depends on contained metal—sensitivity of the expected amount of metal can be estimated from Equation (3) and is shown in Figure 2. A 10% change in mean grade (base change = 1.1 or 0.9) results in a 55% increase (change in expected metal = 1.55) or 35% decrease in expected metal content. Expected metal content changes 10% when there is a 10% change in the expected number of deposits. A 10% variation in mean tonnage results in a 650% increase (not shown) or 85% decrease in expected metal content (Fig. 2). Variation in mean

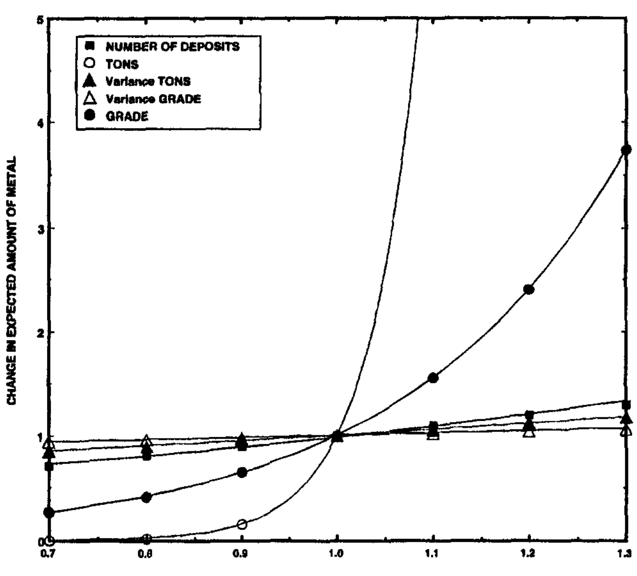

Figure 2. Sensitivity of expected amount of copper in porphyry copper deposits with respect to possible changes in expected number of deposits and means and variances of log tonnage and log copper grade.

tonnage is of overwhelming importance in determining metal content. The greatest opportunity for reducing uncertainty and risk in exploration and resource assessment lies with lowering the uncertainty associated with tonnage estimates followed in importance by uncertainty associated with grade estimates. Although we have assumed that the distribution of deposit sizes and grades can be represented by independent lognormal distributions in Equation (3), any assumed distribution that honors the highly skewed nature of deposit tonnages will produce similar results. Exploration enterprises, therefore, commonly use an economic filter that is made operational by requiring a minimum size deposit.

Identification of minimum size deposits can be addressed by recognizing and using the significant differences in grades and tonnages among different types of mineral deposits (Cox and Singer, 1986; Singer, 1993; Singer, Mosier, and Menzie, 1993). These differences are clearly demonstrated in Figure 3 where, if the objective is locating a world class gold deposit (at least 100 tons of gold), porphyry Cu–Au or epithermal quartz alunite Au deposits require fewer deposits to be examined than Comstock epithermal vein and several other deposit types, all other things being equal.

World-class mineral deposits, defined as the upper 10% of all deposits in terms of contained metal (Singer, 1995), are the primary exploration targets of many mining firms (Kouda and Singer, 1997). About 30% of epithermal quartz alunite Au–Ag deposits contain enough gold to be considered world class, 25% of porphyry copper deposits have enough copper to be considered world class, 30% of Mississippi Valley Zn–Pb districts have enough zinc, 25% of sedimentary exhalative Zn–Pb deposits have enough lead, and 35% of polymetallic replacement districts contain enough silver to be considered world class (Tables 1–5). Because of the high correlation between tonnage of ore and tonnage of contained metal in deposit types (Boldy, 1977; Singer, 1995), many world-class lead deposits are also world-class zinc and perhaps world-class silver deposits. If we are only interested in finding a world-class gold deposit, we can consider the number of deposits by type that must be examined to locate one deposit containing at least 100 tons of gold (Fig. 3). On average, to have a 95% chance of a 100-ton Au deposit, 50 low-sulfide quartz Au vein deposits would need to be examined, 26 Comstock epithermal Au or hot-spring Au deposits, 16 sediment-hosted gold deposits, or 11 porphyry Cu–Au or quartz–alunite Au

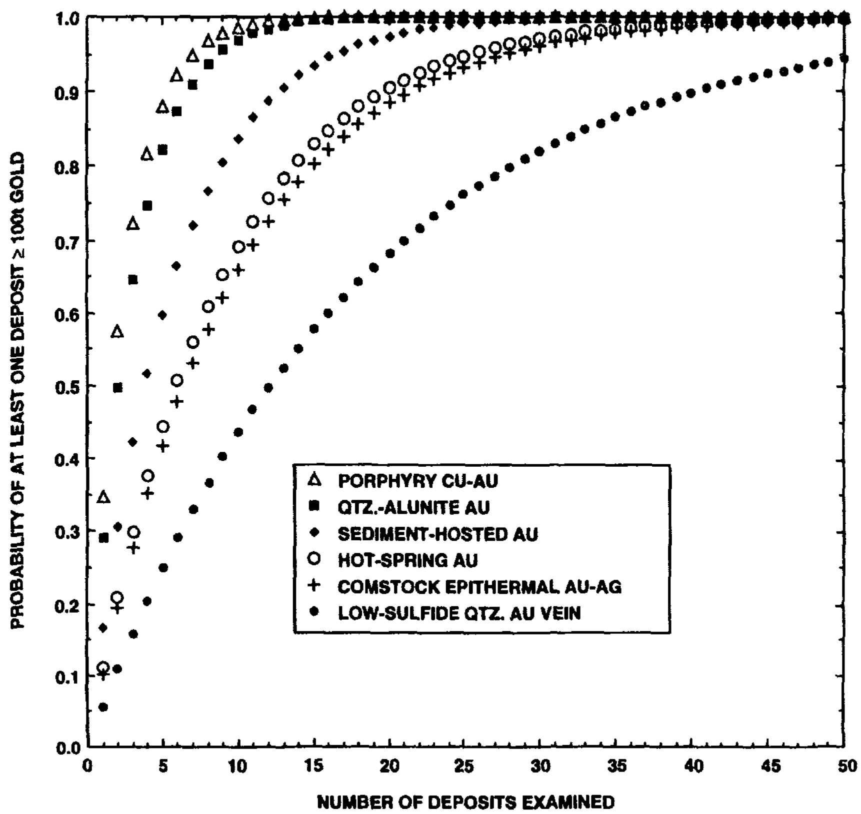

Figure 3. Probability of at least one gold deposit containing at least 100 tons of gold plotted against number of deposits needed to be examined by deposit type. Based on Equation (1) and the percentage of world-class gold deposits shown in Table 1.

deposits. Thus, although the goal is stated in terms of contained metal, the chances of success can be affected by searching for different deposit types, which affects where exploration takes place because of the linkage between deposit types and geologic settings. This strategy was key to Homestake's success in locating the McLaughlin hot-spring gold deposit (Anderson, 1982).

These chances must be weighed against the profitability of different types, abilities of the searchers, number of undiscovered deposits that might exist, areas available for search, and regional or local differences within types. One might elect to search for Mississippi Valley Zn–Pb districts or kuroko deposits of which about 90% of known deposits or districts have been economic, before searching for the 50% economic porphyry copper deposits. If the number of known deposits is proportional to the number of deposits yet-to-be discovered, then one would search for kuroko deposits with about 500 deposits, rather than the 10 times more scarce Mississippi Valley Zn–Pb districts, or the half as abundant porphyry copper deposits.

Risk Reduction Within Deposit Types

The strategy of focusing exploration only on world-class deposits has the advantage that the risk of economic loss from mining an uneconomic deposit is reduced significantly at the expense of having few or no deposits to examine; that is, there may not be any economic world-class deposits remaining to be discovered in a specific exploration setting. There also is the potential loss of deposits that are economic but are not examined because they seem to be smaller than some predetermined size. By increasing economic risk, it is possible to reduce the risk of not finding a mineral deposit. The balancing of economic filters, geologic theory, and the distribution of deposit sizes remaining in an exploration setting provides opportunities for risk reduction.

Experience in petroleum exploration demonstrates that larger deposits tend to be discovered early in an exploration play (Drew, 1990). Locating larger deposits early reduces the sizes and values of remaining deposits and affects discovery chances

Table 1. Percentage of World-Class Gold Deposits by Deposit Type

Deposit type	Number of deposits	Percentage deposits >100 ton gold
Porphyry Au	12	50
Porphyry Cu–Au	69	35
Epithermal quartz alunite Au	24	29
Sediment-hosted Au	48	17
Porphyry Cu	300	14
Hot-spring Au–Ag	27	11
Comstock epithermal vein	166	10
Homestake Au	243	9
Creede epithermal vein	31	6
Low-sulfide Au–quartz vein	413	6
Sado epithermal vein	40	5
Polymetallic replacement	74	3
Au skarn	37	3
Zn–Pb skarn	47	2
Sed. exhalative Zn–Pb	99	1
Kuroko massive sulfide	507	1

because discovery chances are a function of deposit size. In an analysis of petroleum exploration of the Powder River Basin, Wyoming, Drew (1975) showed that some explorationists were able to reduce their risk of failure by about 43% by exploring around the discovery of a large deposit. This risk reduction came at a price of finding only 36% as much oil per hole.

The only published study on metal-bearing deposits showing a pattern of locating larger deposits early in the exploration process was on mercury deposits in California (Chung, Singer, and Menzie, 1992). Epithermal gold deposits in Nevada and carbonatite deposits in Brazil show no relationship between size and discovery order. In both examples, however, large discoveries were made late in the exploration process in areas of difficult access. In the example of carbonatite deposits in Brazil, perhaps the largest deposit, Seis Lagos, was discovered in recent years in the remote headwaters of the Amazon River. The larger Nevada epithermal gold deposits discovered in 1890–1910, such as Round Mountain and Goldfield, are located off the paths to California, which is where most Nevada epithermal deposits discovered in 1840–1870 are located.

It can be shown that for some deposit types, such as, porphyry copper, the larger deposits should be discovered earlier than smaller deposits (Singer and Mosier, 1981). However, this is only true within fixed exploration settings, such as an exposed permissive rock that has all parts equally accessible. The relationship between the size of mineralized area and chance of discovery was used successfully in the search for the Mississippi Valley-type deposit at Elmwood, Tennessee (Callahan, 1977). When the exploration setting changes, for example, looking under shallow cover with a particular technique, then the process of finding larger deposits starts over. Boldy (1977) demonstrates

Table 2. Percentage of World-Class Copper Deposits by Deposit Type

Deposit type	Number of deposits	Percentage of deposits $>2 \times 10^6$ ton Cu
Kipushi Cu–Pb–Zn	2	50
Sediment-hosted Cu	88	28
Porphyry Cu	300	24
Porphyry Cu–Au	69	19
Synorogenic Ni–Cu	33	3
Besshi massive sulfide	47	2
Polymetallic replacement	74	1
Kuroko massive sulfide	507	1

Table 3. Percentage of World-Class Zinc Deposits by Deposit Type

Deposit type	Number of deposits	Percentage of deposits $>1.7 \times 10^6$ ton Zn
Kipushi Cu–Pb–Zn	2	50
Mississippi Valley Zn–Pb	32	31
Sed. exhalative Zn–Pb	99	29
Zn–Pb skarn	47	15
Polymetallic replacement	74	7
Kuroko massive sulfide	507	5
Creede epithermal vein	31	3

Table 4. Percentage of World-Class Lead Deposits by Deposit Type

Deposit type	Number of deposits	Percentage of deposits $>1 \times 10^6$ ton Pb
Kipushi Cu–Pb–Zn	2	50
Sed. exhalative Zn–Pb	99	25
Mississippi Valley Zn–Pb	32	22
Polymetallic replacement	74	22
Sandstone-hosted Pb–Zn	24	17
Zn–Pb skarn	47	11
Kuroko massive sulfide	507	2

Table 5. Percent of World-Class Silver Deposits by Deposit Type

Deposit type	Number of deposits	Percentage of deposits >2400 ton Ag
Kipushi Cu–Pb–Zn	2	50
Polymetallic replacement	74	34
Distal Disseminated. Ag	13	23
Sed. exhalative Zn–Pb	74	16
Creede epithermal vein	31	16
Zn–Pb skarn	47	13
Sediment-hosted Cu	88	10
Epithermal quartz alunite Au	22	9
Mississippi Valley Zn–Pb	32	6
Porphyry Cu	300	6
Comstock epithermal vein	166	5
Sandstone-hosted Pb–Zn	24	4
Kuroko massive sulfide	507	3
Porphyry Cu–Au	69	3
Au skarn	37	3
Cu skarn	70	1
Polymetallic vein	75	1

the effect exploration method has on deposit size discovery order in the search for massive sulfide deposits. Based on an analogy with petroleum exploration, one could reduce the risk of exploration failure by following other's discoveries in a new exploration setting, but expect to find smaller, perhaps uneconomic deposits. Alternatively, one could reduce the risk of locating an uneconomic deposit by focusing on frontier exploration areas and taking advantage of the relationship between the size of deposits and the chance to discover them. Boldy (1977) discusses this trade-off in the search for volcanic-hosted massive sulfide deposits in Canada. An example illustrating these types of possibilities for porphyry copper deposits is presented in Figure 4. Because there is a strong positive relationship between area of sulfides (disseminated pyrite) and the deposits' contained copper, one might only examine large sulfide systems if looking for large porphyry copper deposits. About 75% of the world-class deposits (i.e., greater than 2 million tons of copper) in Figure 4 are economic, whereas, only 30% of the smaller deposits are economic.

An example using kuroko massive sulfide deposits serves to demonstrate how regional or local differences within a type can be identified and used in an exploration strategy designed to reduced risk (Singer, 1996). Massive sulfide deposits associated with felsic to intermediate submarine volcanic rocks are herein classed as kuroko deposits. Tonnages of 424 kuroko deposits from around the world, along with published rock compositions and rock textures up to 500 above and 500 m, beneath these deposits (Mosier, Singer, and Salem, 1983), were used for this analysis. An analysis of variance method was used on the deposits with the logarithm of tonnage as the dependent variable. The only significant effect for rocks above kuroko deposits is an increased tonnage where the hanging wall rocks are sedimentary. Kuroko deposit tonnages also significantly increase where there are sedimentary or rhyolitic footwall rocks. Although only 8% of kuroko deposits are world class, the explorationist can improve these odds significantly, to about 15%, by looking in special geologic settings such as those containing sediments and rhyolitic rocks.

Risk Reduction from Political and Security Sources

The risk of investment or personnel loss because of instability of a government can be the key factor in an exploration decision. As pointed out in an article in the *Mining Journal* (13 March 1998), there are countries where the government has ceased to function or where the government is unable to maintain law and order. Expropriation may be a risk in some countries.

Among the ways to reduce political or security risk are to involve investors who are unlikely to be expropriated, to avoid countries where the risk is high, or to require a high rate of return on an investment. A high rate of return translates into a short payback period—thus shortening the exposure period and, if there are many independent investments, reduces the average risk of loss. Because poverty and the distribution of income are at the root of instability in some countries, requiring a high rate of return may add to instability by breeding resentment.

Risk Reduction from Economic Sources

Most risk of failure for economic or technical reasons stems from commodity prices being lower than expected, ore reserves being lower than estimated, costs being higher than estimated, beneficiation difficulties, such as poor recovery, currency exchange rates, or delayed development. Acts of nature, such as floods, also introduce risk as shown by the drought at the Ok Tedi mine in Papua New Guinea in 1997. Some

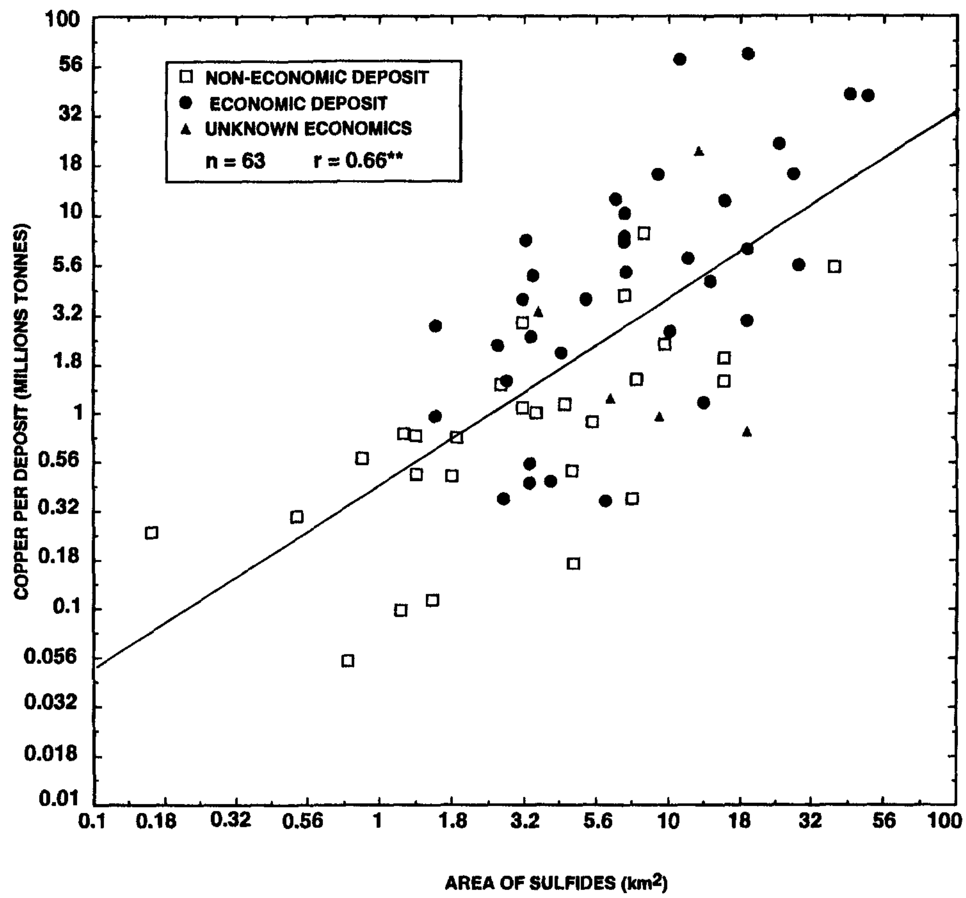

Figure 4. Area of sulfides vs. contained copper in porphyry copper deposits.

recommend that risk be adjusted for by increasing the economic return required for an investment. This strategy is suitable only where there are multiple investments with independent risk factors. In mineral exploration and development there are other, more specific, actions that can be taken to reduce risk.

For large low-grade deposits, errors in grade estimates are a major source of risk. Reliability of grade and tonnage ore-reserve estimates is typically a function of the amount of information gathered. If actual grades or tonnage are below certain values, the deposit will be uneconomic; that is, there will be economic loss. Drilling more holes both decreases the expected value of the deposit and reduces the uncertainty of the value of the deposit. The marginal benefit of obtaining more information to reduce the risk of a bad investment must be balanced against the costs in money and time of gathering additional information (Mackenzie, 1994).

Large variation in commodity prices is usual in the mineral industry. Effects of different prices on the economics of mining can be shown by moving the positions of the mines in Figure 5 up or down to reflect the appropriate price change (Singer, Menzie, and Long, 1998). Thus, if the price of gold were only 80% of the $380/oz used to plot the mines in Figure 5, then the mines need be moved downward only to 80% of their present height to show the effects of this lower price, assuming no revision of reserves. The boundaries between economic, marginal, and noneconomic do not change with commodity price changes. Changes in the rate of return affect the positions of the boundaries, but a change from 15 to 5% lowers both lines—$0.70 a ton, at most, and would be barely noticeable if plotted in Figure 5. However, $0.70 a ton makes a big difference if you process millions of tons and, therefore, is important in determining profitability of a potential mine.

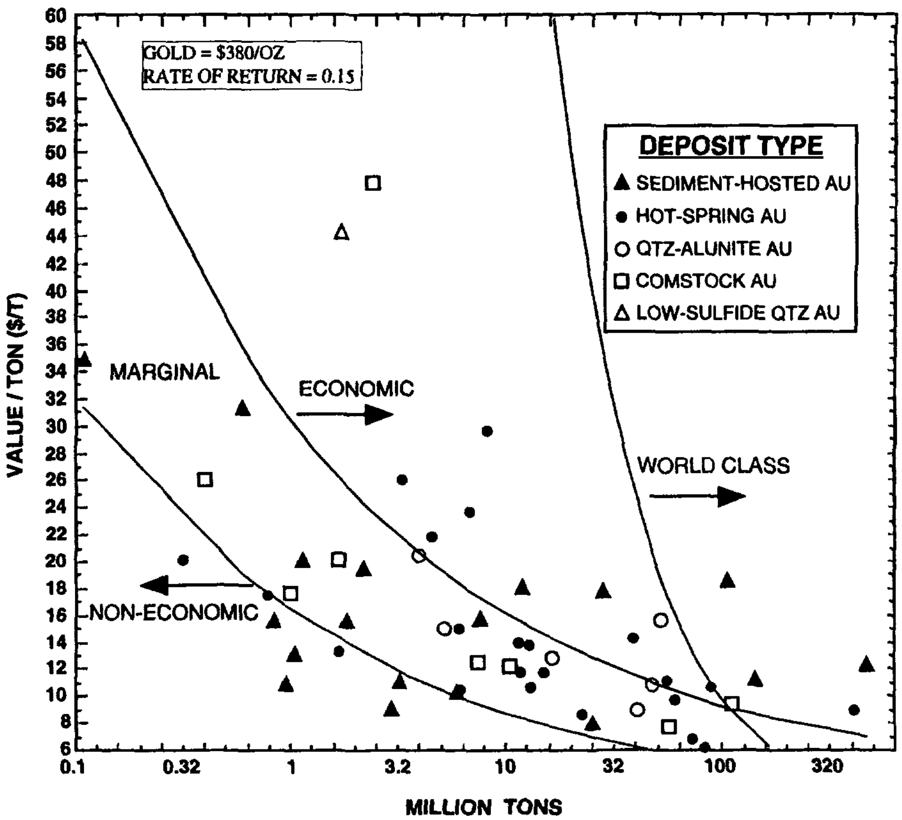

Figure 5. Relationship between value per short ton and deposit size (tons of ore) for U. S. open pit, gold–silver deposits. Economic filters of 0.7 and 1.3 of break-even values for heap-leach operations and based on gold price of $380/oz, silver price of $5/oz, and 15% rate of return. Also plotted is line representing world-class deposits containing at least 100 tons of gold.

This illustration (Fig. 5) shows clearly why world-class gold deposits are sought as exploration targets—world-class deposits plot well to the right of the upper economic filter. This sort of analysis helps in the consideration of whether a deposit is economic to mine, but there is also price variation during mining that can close a mine.

Variation of prices during the mine's life can be controlled effectively by hedging. Thus, for some or all of the mine's future output, a contract is agreed to for the sale to a specific customer for a fixed price. In addition to such forward sales, various options contracts may be bought and sold in a hedge strategy. When prices fall after the agreement, the seller is viewed as wise, but the converse also is true—both the buyer and the seller have reduced uncertainty for a price.

Another method of reducing risk associated with metal price variability is to seek mineral deposits which contain multiple metals in the hope that when one metal price declines, the other metal prices may move higher. For some periods of time, metal prices move independently or even inversely, but, for the long term, many tend to move together, thus reducing any risk reduction function.

Although not part of exploration, it is possible to reduce the risk of loss in mining by sequentially developing and expanding a mine—thus reducing the capital exposed at early stages and reducing the present value of that risked capital. This strategy also might be effective where there is risk of loss because of governmental instability. Some mining and processing methods such as open-pit, heap-leach, or underground stoping are particularly convenient for this strategy. Because this strategy is easier to employ in some types of mineral deposit than in others, it can play a role in risk reduction in the exploration stage by affecting deposit types sought. Sediment-hosted gold deposits are an example of a type ideal for sequential development—Carlin's mining rate sequentially was increased to 12 times as many tons per year over a 25-year period and Jerritt Canyon's rate was increased to five times as much over an 11-year period.

RISK REDUCTION BY USE OF PRIOR INFORMATION AND BY LEARNING

Up to this point, we have assumed that the probability of discovering a deposit is unrelated to the success or failure of previous examinations. Information on the results of early exploration can be used to adjust the views about the existence of a deposit greater than some size. Let D = a deposit of size X or larger exists; d = a deposit of size X or larger does not exist; B = a deposit of size X or larger is found; and b = a deposit of size X or larger is not found. The probability of missing a deposit given that it exists can be considered the risk and be represented as

$$\beta = P(b|D) \tag{4}$$

Using Bayes' formula, we can determine the probability that a deposit of size X exists, given that it was not found

$$P(D|b) = P(b|D)\,P(D)/(P(b|D)\,P(D) + P(b|d)\,P(d)) \tag{5}$$

Because $P(b|d) = 1$ and $P(d) = 1 - P(D)$, we can simplify Equation (5) (Gilbert, 1987) to

$$P(D|b) = \beta\,P(D)/(\beta\,P(D) + 1 - P(D)) \tag{6}$$

Figure 6 shows the affects resulting from changes in the probability of missing a deposit as calculated from Equation (6). For example, if the prior probability of a deposit existing is 0.5 and the probability of missing is 0.5, Equation (6) provides a revised probability of existence, given failure to find of 0.33. However, if the conditions are the same except that the probability of failure is 0.1, the revised probability of existence becomes 0.09. Revisions of existence probabilities are most noticeable where the prior probability is greater than 0.5 (Fig. 6). Using Equation (6) and Figure 6, we show the effects of learning about the success or failure of past trials and changing the probability of the existence of a deposit with that information. This, in turn, would change the probability of detection of a deposit in the next trial.

In Equation (1) where we examined the basics of risk, we made an assumption that the results of one coin toss have no effect on the next coin toss—this assumption allowed us to examine exploration risk reduction by brute force. There is another form of learning where understanding of the geology and deposit model might be modified as exploration progresses. This form of learning, if successfully applied, can have a profound effect on reducing risk in exploration—poorly applied, it can lead to complete failure. The key to successful application of this form of risk reduction is the nature of the exploration organization. Clearly, organizational culture needs to encourage learning and willingness to reject present models if warranted and yet maintain focus. Rose (1992) discusses organizational traits that adversely affect profits in petroleum exploration firms—many involve risk aversion behavior that discourages the learning that can perhaps most significantly reduce exploration risk.

SUMMARY

Risk in mineral exploration is examined so the sources of risk can be identified and incorporated in the decision-making process in order to reduce controllable risk. Risk is defined as the chance of failure or loss. Exploration is an economic activity involving risk and uncertainty. Thus risk also must be defined in an economic context. Both expected monetary values and the probabilities of various outcomes, such as economic failure, should be considered in the decision-making process. Because economic return, when measured by net present value, is related closely to the size of mineral deposits and deposit sizes are represented by highly skewed frequency distributions, achieving expected monetary or higher values tends to be a low-probability outcome. This and the typical rareness of mineral deposits are the principal reasons for high risk in mineral exploration.

Risk reduction focuses on the strategies using geology, economics, and statistics. A fundamental way to reduce risk is by increasing the number of prospects examined, such as used in the discovery of Elmwood, Tennessee (Callahan, 1977). Joint venturing, where exploration expenses, responsibilities, and benefits are shared among companies is the most common way to take advantage of this method of risk reduction.

A second fundamental way of risk reduction is to reduce the probability of failure per prospect. Balancing of economic filters, geologic theory, and the distribution of deposit sizes remaining in an exploration setting provides opportunities to lower the probability of failure per prospect. The greatest opportunity

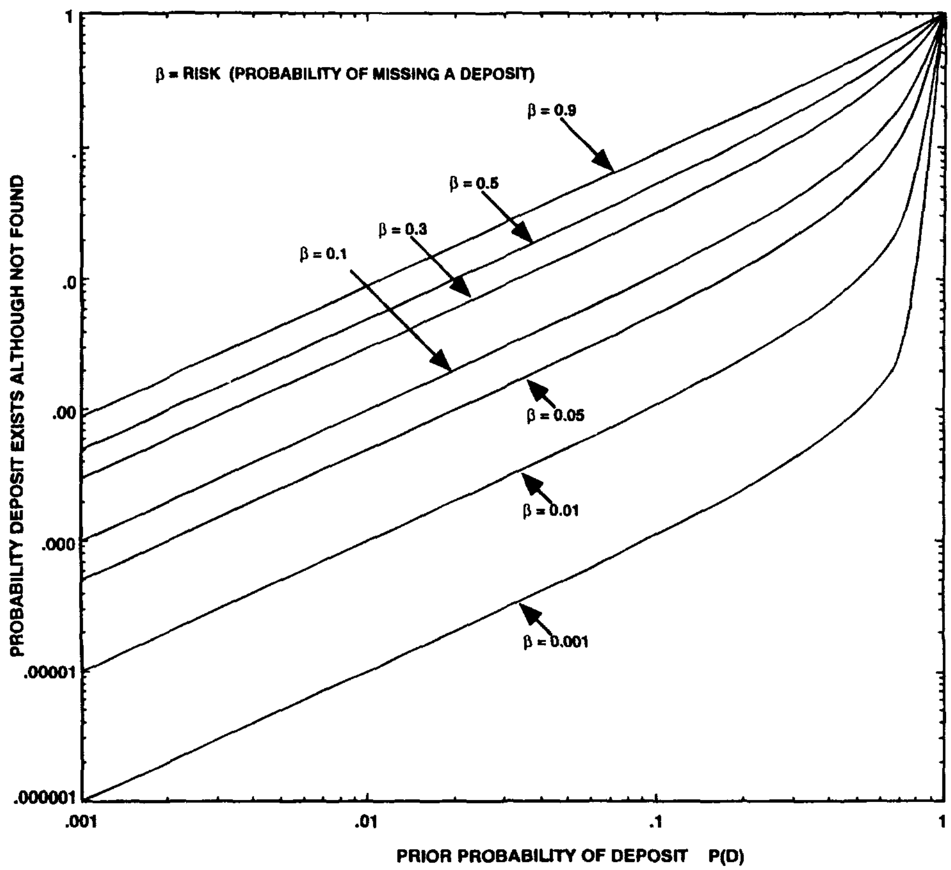

Figure 6. Relationship between probability of existence of deposit given that it has not been found, prior probability that deposit exists, and probability of missing deposit.

for reducing uncertainty and risk in exploration and resource assessment lies with lowering the uncertainty associated with tonnage estimates, followed in importance by uncertainty associated with grade estimates. Exploration enterprises, therefore, commonly use an economic filter that is made operational by requiring a minimum size deposit. This is why world-class mineral deposits are the primary exploration targets of many mining firms. Identification of minimum size deposits can be addressed by recognizing and using the significant differences in grades and tonnages among different types of mineral deposits. For example, a sediment-hosted gold (Carlin type) deposit is more likely to be world class than is a low-sulfide quartz gold vein deposit.

Experience in petroleum exploration demonstrates that larger deposits tend to be discovered early in an exploration play. Finding larger deposits early reduces the sizes and values of remaining deposits and affects discovery chances. Some petroleum explorationists have reduced their risk of failure by using the strategy of exploring around discoveries of large deposits. This risk reduction comes at a price of finding less oil per hole. Based on an analogy with petroleum exploration, one could reduce the risk in mineral exploration by following others' discoveries in a new exploration setting, but the explorationists should expect to locate smaller, perhaps uneconomic, deposits. Alternatively, one could reduce the risk of finding uneconomic deposits by focusing on frontier exploration areas and taking advantage of the relationship between the size of deposits and the chance to discover them.

Use of geology can be helpful in reducing risk in exploration. For example, although only 8% of kuroko deposits are world class, the explorationist can significantly improve these odds to about 15% by looking in special geologic settings, such as those containing sediments and rhyolitic rocks.

Most risk of failure for economic or technical reasons stems from commodity prices being lower than expected, ore reserves being lower than estimated, costs being higher than estimated, beneficiation difficulties such as poor recovery, currency exchange rates, or delayed development. Some recommend that risk be adjusted for by increasing the economic return required for an investment. This strategy is suitable only where there are multiple investments with independent risk factors. Variation of prices during the mine's life can be controlled effectively by hedging. Another method of reducing risk associated with variability of metal prices is to seek mineral deposits that contain multiple metals in the hope that when one metal price declines, the other metal prices may move higher. Although not part of exploration, it is possible to reduce the risk of loss in mining by sequentially developing and expanding a mine—thus reducing the capital exposed at early stages and reducing the present value of that risked capital. Some mining and processing methods such as open-pit, heap-leach, and underground stoping are particularly convenient for this strategy. Because this strategy is easier to employ in some types of mineral deposit than in others, it can play a role in risk reduction in the exploration stage by affecting deposit types sought.

The third fundamental way to reduce risk is to use prior information to modify estimates or to change the assumption of independence in Equation (1), that is, to learn. With Bayes' formula, the effects of learning about the success or failure of past trials can be used to change the probability of the existence of a deposit. This, in turn, would change the probability of detection of a deposit in the next trial.

Other forms of learning are where geologists learn through training or the experience of others or where understanding of the geology and deposit model might be modified as exploration progresses, such as in the discovery of McLaughlin (Anderson, 1982). This form of learning, if successfully applied, can have a profound effect on reducing risk in exploration—poorly applied, it can lead to complete failure.

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