# Linking Mineral Systems Models to Quantitative Risk Analysis and Decision-Making in Exploration

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# Abstract

This paper describes a methodology of translating mineral deposit models into flexible probabilistic structures that are based on the critical processes of ore formation: (1) extraction of ore components (fluids, metals and ligands) from crustal or mantle sources or both; (2) fluid- or melt-assisted transport of ore components from source to trap zones; (3) formation of trap zones (i.e., effective melt or fluid channels) that can focus melt or fluid migration and accommodate large amounts of metal; and (4) operation of the physicochemical processes that promote and sustain the deposition of metal from fluids or melts passing through a particular trap site. Our approach integrates these critical mineralization processes and conditions with concepts of probability theory, decision analysis and financial modeling. The principal objective is to make mineral deposit models amenable to financial risk and value analysis and suitable for communication of value-creating geological concepts to financial stakeholders in economic terms. A case study, based on an actual porphyry copper project, illustrates how the probabilistic mineral systems model can generate a measure of the probability of ore occurrence as an input for exploration decision trees and simulations to calculate the expected value (EV) of an exploration project and the probability distribution of all possible surrounding NPV values within a minimum and maximum range. Formulation of the probabilistic model closely follows and combines principles of the well-established petroleum and mineral systems approaches and makes use of Excel™-based model templates with decision tree and simulation add-in software packages.

# Introduction

Mineral exploration is an economic activity and as such is expected to provide an acceptable return to those who invest in it (e.g., Singer and Kouda, 1999; Lord et al., 2001). However, the probability of success in mineral exploration is generally so low and the attendant geological uncertainty so high that it has always been very difficult for investors and exploration managers to consistently manage programs to improve the chance of financial success (e.g., Rose, 1987) in a cost-effective manner. Some recent studies of the financial performance of the business of mineral exploration have concluded that it is, at best, a break-even proposition but more likely a loss-making investment (e.g., Eggert, 1993; Schodde, 2004; Leveille and Doggett, 2006). This study examines ways to improve the ability to manage mineral exploration for better financial performance.

Recent financial modeling indicated that there are three principal levers that control the return on exploration investment at the portfolio and program levels (Etheridge et al., 2006): (1) the number of projects effectively tested and turned over; (2) the average expenditure per project (especially on those that failed); and (3) the average probability of success across the portfolio. The industry attempts to improve the probability of success by applying superior geoscience and allocating its investment dollars to the best projects. A range of project ranking schemes are used to identify the most promising projects. At the core of most schemes, and indeed much of our exploration judgment, are mineral deposit models that describe the characteristics that are considered by the author(s) of the model to represent key aspects of the type of mineral deposit that is sought within a particular setting. Although generally referred to as either conceptual or empirical, most of the widely used models include a variably complete array of process factors for ore-formation, products of the mineralization process, characteristics of the regional and local geology and structure, inferences about the tectonic setting, and grade and tonnage data (e.g., Ludington et al., 1985; Cox and Singer, 1986; Hodgson, 1993; Barton, 1993; Henley and Berger, 1993; Thompson, 1993; Hronsky, 2004; Sillitoe and Thompson, 2006). Wyborn et al. (1994), Knox-Robinson and Wyborn (1997), McCuaig and Hronsky (2000) and Hronsky (2004) advanced and promoted the mineral systems concept with deposits being the focal points of much larger systems of energy and mass flux. The implications of the mineral systems concept are that the parameters that control size and location of deposits also are aspects of these large-scale systems, and that mineral deposit models are of predictive value only if they incorporate the ore-forming processes at all scales of the mineral system. This study adopts a mineral system approach.

The concept of a mineral system is based closely on the petroleum systems model (Magoon and Dow, 1994) that has unified exploration geoscience, project ranking and portfolio investment management in the petroleum industry. A key factor in the broad and rapid uptake of the petroleum systems model has been that it is amenable to practical probabilistic risk and value analysis and to decision-making. The implementation of quantitative methods of risk and decision analysis by petroleum companies since the late 1980s and early 1990s has brought greater objectivity and consistency to the valuation of their project inventories. It has also led to adoption of economic yardsticks and risk and reward definitions in selecting annual exploration portfolios and, ultimately, resulted in improved exploration and financial success (e.g., Rose, 1999; McMaster, G., 2003 [1]; Gouveia et al., 2003 [2]; Suslick and Schiozer, 2004). Applications of probabilistic statistical methods have also been successful in the search for the lost submarine USS Scorpion (Sontag and Drew, 1998), and in reducing the cost and increase the efficiency of drug and medical device trials, increasing the effectiveness of ‘data mining’ techniques and setting catch limits for fish (e.g., Malakoff, 1999).

The work described in this paper was part of a multidisciplinary, industry-collaborative research project at Macquarie University, designed to investigate and develop ways to improve management of risk, uncertainty and value creation in mineral exploration. We offer a methodology that links our understanding of ore-forming processes to flexible probabilistic decision-making tools that (1) promote systematic estimation of geological uncertainty, (2) are amenable to probabilistic risk and value analysis and (3) can convert our geological concepts to successful business models as is routinely done in the petroleum industry. The overall aim of this paper is to demonstrate that probabilistic mineral systems models are superior to the widely used mineral deposit models in terms of flexibility, quantitative analysis of risk and uncertainty, and communication of value-creating geological concepts to managers and financial stakeholders. Formulation of the probabilistic mineral systems models closely followed the principles of the petroleum (Magoon and Dow, 1994) and mineral (Wyborn et al., 1994) systems approaches, and the approach to measuring exploration success by Lord et al. (2001).

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[1] McMaster, G., 2003, Merging risk assessment and portfolio management: the search for value: www.gsspe.de/events/mcmaster/DistLectCirculate1.ppt

[2] Gouveia, J., Rose, P., and Gingerich, J., 2003, The prospector myth – coming to terms with risk management in mineral exploration: www.pdac.ca/pdac/publications/papers/2003/Gingerich-Risk.pdf

## Definition of the Terms Risk and Uncertainty

In the broader context of risk management the term risk generally combines the likelihood of an event occurring and the consequences of the event should it occur. This definition is embedded in various risk management standards and usually presented as matrix of likelihood against consequences (e.g., Clemens and Pfitzer, 2006). We follow the practice of the petroleum industry where exploration risk is defined as the probability of a project delivering a negative financial consequence. In this context risk may be defined as the probability of failure and is equal to one minus the probability of success (e.g., Singer and Kouda, 1999; Murtha, 2000).

Uncertainty is a measure of our inability to assign a single value to a possible event and defined as the variability of possible events around their mean (expected) value. The quantification of uncertainty is the difference between the true value of a natural outcome and an estimate of its value. Biases occur when values are systematically under- or overestimated (e.g., Bárdossy and Fodor, 2001).

## Previous Approaches to Geological Process Modeling

### *The petroleum systems approach*

A petroleum system includes all elements and processes that are necessary to generate and store hydrocarbons. It is a natural system that exists wherever the distribution of petroleum source, reservoir, seal and overburden rocks was linked in space and time with trap formation and the generation, migration and accumulation of hydrocarbons (Magoon and Dow, 1994). The stratigraphic, geographic and temporal extent of petroleum systems is displayed in petroleum system maps, schematic cross-sections and burial history diagrams, whereas the components of petroleum systems and their critical timing relationships are recorded in petroleum events charts (e.g., Smith 1994; Demirel, 2004; Sarmiento and Rangel, 2004). Given that the petroleum systems model is process-based and considers all process components that are necessary to form a commercial deposit, it is now widely used to manage geological uncertainty and exploration risk by (1) determining the spatial and temporal distribution of the essential elements and processes, (2) gaining an understanding of where the petroleum came from and how it migrated, (3) predicting the places where petroleum is most likely present, and (4) estimating the quantity of the petroleum that was generated and trapped (e.g., Magoon and Dow, 1994; Smith, 1994; Newendorp and Schuyler 2000; Suslick and Schiozer, 2004).

### *The mineral systems approach*

The mineral systems approach (e.g., Wyborn et al., 1994; Knox-Robinson and Wyborn, 1997; Hagemann and Cassidy, 2000; Huston, 2000; Huston et al., 2004) promoted by Geoscience Australia is essentially an adaptation of the petroleum systems approach of Magoon and Dow (1994). Although mineral systems are generally perceived as being more diverse and complex than petroleum systems, the critical parameters of ore formation can be reduced to (1) a source of energy that drives the system, (2) sources of fluids, metals and ligands, (3) pathways along which fluids can migrate to trap zones, (4) trap zones (i.e., narrow, effective pathways) along which fluid flow becomes focused and fluid composition is modified, and (5) outflow zones for discharge of residual fluids (see fig. 3 in Knox-Robinson and Wyborn, 1997). Ore formation is precluded where a particular mineral system lacks one or more of these essential components. Being process-based, the application of the mineral systems approach is neither restricted to a particular geological setting nor limited to a specific mineral deposit type; indeed, multiple mineral deposit types can be realized and tested within a single mineral system (e.g., Wyborn et al., 1994; Knox-Robinson and Wyborn, 1997; Hagemann and Cassidy, 2000). Applied to mineral exploration, the mineral systems approach requires identification at various scales of the critical ore-forming processes and mappable features that characterize a particular mineral system (e.g., Wyborn et al., 1994).

### *The probabilistic approach*

The probabilistic approach to process modeling of Lord et al. (2001) requires the following actions: (1) formulation of an underlying geological process model; (2) identification of the independent, critical success factors ($P_1$ = ore component sources, $P_2$ = fluid conduits, $P_3$ = trap sites, and $P_4$ = physico-chemical processes at the trap sites); (3) assignment of probabilities to each factor; and (4) application of the multiplication rule (e.g., Megill, 1988) to obtain an overall probability of success (i.e., that potentially economic mineralization is present at the location of interest) ($P_{Mineralisation} = P_1 \times P_2 \times P_3 \times P_4$).

By integrating process-based mineral deposit modeling and aspects of probability theory, Lord et al. (2001) created a powerful tool for quantitative ranking and evaluation of exploration projects and assessment of exploration strategy and performance. Owing to the numerical output, the probabilistic approach of Lord et al (2001) promotes communication of geological uncertainties and technical and financial risk.

## New Probabilistic Mineral Systems Models

Background information on the software and quantitative methods used in this paper is given in Appendix 1, including the basic concepts of probability theory, Bayesian (conditional) probability and the expected value (EV) concept. A schematic overview of the approach is given in Figure 1.

### *Modeling step 1: Formulation of mineral systems models*

The first step in the modeling approach is to list the critical processes that must operate for ore deposition to occur within a particular area (cf. Wyborn et al., 1994; Lord et al., 2001; Penney et al., 2004). These are (1) extraction of ore components such as fluids, metals and ligands from crustal or mantle sources, (2) fluid- or melt-assisted transport of ore components from source regions to trap zones (i.e., effective melt, fluid or vapor channels), (3) formation of trap zones that are sufficiently wide to accommodate large amounts of metal but narrow enough to efficiently focus melt or fluid migration during protracted or brief and repetitive events of energy an mass flux, and (4) operation of the physicochemical processes that promote and sustain the deposition of metal from melts, fluids or vapor passing through a trap zone. We propose that the critical processes are similar for most, if not all, mineral deposit types. The key to the inherent natural diversity of mineral deposits lies in the diversity of the critical subprocesses, essential elements and four-dimensional extent. These factors can be extremely variable, even for adjacent mineral deposits of similar style (e.g., sulfide-rich and sulfide-poor lode-gold deposits, Kolar goldfield, India: Mishra and Panigrahi, 1998).

Appendix 2 gives examples of mineral system models and model templates for lode-gold, porphyry-copper, nickel-sulfide and stratiform lead-zinc deposits that are based on our assessment of the current state of knowledge. These models were used to develop and test the probabilistic mineral systems model presented in this paper and serve as examples of how to assign critical processes and subprocesses of ore formation to the model template.

### *Modeling step 2: Design of mineral systems model templates*

The model sheets in Appendix 2 are indented as frameworks for the systematic compilation and development of a comprehensive knowledge base of the factors that are critical in and lead to the formation of the targeted mineral deposit style within a particular area of interest. The model sheets consist of five parts: (1) the essential elements of the mineral system (model part 1); (2) the critical processes (model part 2A) and subprocesses (model part 2B) that must operate for ore deposition to occur within a particular area; (3) the four-dimensional extent of the ore-forming system (model part 3); (4) post-ore processes (model part 4) such as outflow of spent fluids from trap zones, upgrading of mineral systems by supergene or metamorphic processes, and preservation of mineral systems through time; and (5) decision-making (model part 5) (i.e., to drill test, seek further information via an additional targeting technique, or abandon a project).

### *Modeling step 3: Transfer of model templates into analysis software*

The mineral systems models were programmed into Excel™ spreadsheets for use with standard, add-in risk analysis software such as @RISK™ and PrecisionTree™ by Palisade Corporation (see www.palisade.com for further information), Crystal Ball™ by Oracle Corporation (www.crystalball.com) and RiskSim™ and TreePlan™ by Decision Toolworks (www.decisiontoolworks.com).

### *Modeling step 4: Assignment of probabilities to processes of ore formation*

In the spreadsheet of Figure 2, the user (1) determines whether or not particular subprocesses operated within a particular area, and (2) assigns either single probabilistic values (on a scale from 0.0 to 1.0) or ranges of likely values, based on geological evidence for the subprocess having operated at the location of interest. Where a range of probabilities is assigned, the values are assigned a uniform distribution that is characterized by the extremes of the range (i.e., minimum and maximum) and has constant probability (i.e., all values of the distribution are equally probable). This distribution is sampled randomly during subsequent simulations of the system (modeling step 7). To standardize subjective probability estimates we recommend the use of calibrated scales, such as the Sherman-Kent scale (e.g., Jones and Hillis, 2003; Table 1). Examples of assigning probabilities are described in a case study below.

The probability of a critical process (e.g., $P_1$ to $P_4$ in Fig. 2) having operated is the product of the probabilities assigned to the each critical subprocess. By multiplying $P_1$, $P_2$, $P_3$ and $P_4$, a probability of occurrence of potentially economic mineralization ($P_{Mineralization}$) can be obtained for a particular location (Lord et al., 2001). In this analysis, the probability of occurrence of the critical processes of ore formation at a particular location is independent of historic exploration or mining or other estimates of mineral deposit occurrence. Hence, we argue that a 100 per cent fit to the probabilistic mineral systems model (i.e., $P_{Mineralisation} = 1.0$) is an indication for a mineral deposit definitely having formed at a particular location. To obtain a $P_{Mineralisation}$ of 1.0, the user would have to assign probabilities of 1.0 to all critical subprocess, and thus would have to have unambiguous evidence for all subprocesses, including those that are linked directly to the scale and intensity of metal deposition (e.g., $P_{3B}$ and $P_{4B}$ in Fig. 2), having occurred. If, on the other hand, we assign a probability of 0.0 to one or more of the critical subprocesses, the chance of ore occurrence becomes zero. By assigning a probability of 0.5, we acknowledge that it is equally likely that a subprocess did or did not operate within a particular project area.

A particular mineral system can only exist where the distribution of its essential elements was linked in space and time with the critical processes of ore formation. Identification of this spatial and temporal link and determination of the critical processes of ore formation are the keys to (1) exploration targeting, which concentrates on areas where this link can be demonstrated, and (2) data compilation, which focuses on collecting evidence for the critical processes and subprocesses of ore formation having occurred within these areas of interest. This approach differs from the traditional mineral deposit models, which exploration geologists use as guidelines while focusing on evidence for mineralization processes to discover ore (e.g., McCuaig and Hronsky, 2000). The probabilistic mineral systems models help to keep track of and measure the degree of fit of the model elements to specific cases.

### *Modeling step 5: Definition of exploration cost and value distributions*

All monetary values in our probabilistic decision model are linked to cost and value inputs or their probability distribution functions (Fig. 1) that were either estimated or fitted to historical datasets using risk analysis software. These distributions are contained in an assumptions worksheet.

The possible costs of exploration (i.e., surveying, drill testing and resource delineation) and feasibility are defined by the parameters of triangular distributions (minimum, most likely, maximum) that are user inputs and adjustable to suit particular company estimates or cost structures.

Three databases of the value of mineral deposits were used in the probabilistic decision model (Fig. 1, Table 2). The datasets of the Metals Economics Group include acquisition values of all gold and base metal (n = 343) projects for which transactions were recorded between 1993 and 2003. By having removed from this database any projects that had commenced mining, we obtained a subset of values for projects at exploration stages ranging from B to E of the exploration process as defined by Lord et al. (2001) (Table 3). For comparability all transactions were grossed up to full project value and converted to Australian dollars at 2004 values. The dataset of Schodde (2004) Australian gold discoveries (n = 59) between 1985 and 2002 is a record of the net present value (NPV) of these discoveries at the time of the decision to mine. These NPVs, expressed at 2003 Australian dollar values, were calculated using generalized project capital and operating cost estimates, a gold price of Australian dollars 550 per ounce and the tax rules of 2003. The dataset of Leveille and Doggett (2006) of global copper projects (n = 65) discovered and developed between 1992 and 2004 includes calculations of their NPVs in US dollars at 2004 values. The underlying cash flows are based on average metal prices over the period 1992 to 2004, an effective tax rate of 30 per cent and are discounted at a rate of 8 per cent. These three datasets are fitted well by the lognormal distribution and this is consistent with the commonly lognormal distribution of mineral deposit grade and tonnage data (e.g., Folinsbee, 1977; Singer, 1993; Rose, 1999). A good fit was confirmed by goodness-of-fit tests such as Chi-Square, Anderson-Darling and Kolmogorov-Smirnov, using risk analysis software.

### *Modeling step 6: Integration of the mineral systems model templates with an exploration decision tree*

Decision trees are widely used for structuring, analyzing and quantifying investment decisions in sequential chronological order and calculating their EVs in terms of the probability of occurrence and monetary reward of all possible outcomes (e.g., Newendorp and Schuyler, 2000; Clemen and Reilly, 2001). In step 6 of our modeling approach, the spreadsheet-based mineral systems models are used as inputs in a decision tree (Figs. 1 and 3) that follows the conventions outlined in Newendorp and Schuyler (2000), Murtha (2000) and Clemen and Reilly (2001) and incorporates Monte Carlo simulation capability.

The tree in Figure 3 is intended to calculate the EV of exploration projects that are at stage B of the exploration process as defined by Lord et al. (2001); that is the ground has been acquired, a geological knowledge base has been established and drillable targets have been or are being identified. The underlying maximum time frame is the number of years required for successful completion of exploration stages B to D (Lord et al., 2001;

Table 3), concluding with the delineation of a potentially payable resource that can either be mined or sold.

The exploration decision tree offers three main decision paths: (1) drill, (2) apply additional targeting technique, or (3) terminate. Decision path 1 (Fig. 3) is based on the scenario where a company has identified a target with a $P_{Mineralisation}$ value (as described in modeling step 4) that is at a level justifying immediate drill testing. Decision path 2 (Fig. 3) is tailored to the situation where the $P_{Mineralisation}$ of a target is below the level required to justify immediate drilling, but where the application of an additional geochemical or geophysical targeting method is expected to result in a revised and improved $P_{Mineralisation}$ that would warrant drill testing. This posterior or updated $P_{Mineralisation}$ is calculated using Bayes' rule of conditional probability (Appendix 1). Decision path 3 (Fig. 3) reflects the scenario where, in spite of skillful exploration, no drillable targets are defined, and where the application of further targeting techniques is perceived as futile.

Pay-off values, computed for each decision path in the decision tree, represent the EVs of the three exploration strategies outlined above. A positive EV indicates that the corresponding exploration strategy is likely to be successful whereas a negative EV justifies rejecting the underlying decision alternative.

### *Modeling step 7: Monte Carlo simulation*

The final step in the modeling approach is a Monte Carlo simulation (e.g., Morin and Ficarazzo, 2006) of the exploration decision tree where input value probability distributions (i.e., uniform: $P_{Mineralisation}$; triangular: costs of exploration, sale prices;

lognormal: value of mineral deposits) that describe the model inputs are sampled at random up to several tens of thousands of times. Each simulation step represents an individual possible outcome and is aggregated into the final result: a statistical distribution of possible NPVs of the modeled project that surround their mean (“base case”) EV (Fig. 1).

## A Porphyry Copper Case Study

This case study is a real world application of the probabilistic mineral systems modeling approach to an undisclosed porphyry copper-gold project. To come up with a structure for calculating the EV of this project, the project owner modified the exploration decision tree. Monetary values in this case study are in nominal US dollars and results are based solely on the assessment of the geological risk factors.

### *Prospect characteristics*

The prospect is located within a metallogenic province comprising rock assemblages and mineral deposits that are typical for magmatic island-arc environments. Three economically mineable porphyry copper-gold systems containing between 250 and 1000 million metric tons of ore at grades ranging from 0.3 to 0.6 per cent copper and 0.3 to 0.8 g/t gold have previously been discovered within this province. The prospect is situated along strike of and mid-way (i.e., 40 km from each) between two of these significant porphyry copper-gold deposits. The province also contains numerous copper-gold skarn occurrences but they are commonly much smaller and of inferior value compared to the porphyry copper-gold deposits. In addition, the copper-gold skarn occurrences can cause false positives that can set porphyry copper-gold exploration efforts on the wrong track.

The prospect being valued in this case study is defined by copper (>200 ppm), gold (>1000 ppb) and molybdenum (>10 ppm) geochemical anomalies in soils over an area of approximately 800 by 600 m. The anomalous molybdenum values are an important predictor of the style of mineralization likely to be present within the project area given that porphyry copper-gold deposits within the belt are molybdenite-bearing, whereas the copper-gold skarns are not. The copper, gold and molybdenum anomalies at the prospect are flanked by zones of elevated lead and zinc values. This metal zonation pattern (Cu, Au, Mo → Pb, Zn) is typical for intrusion-related deposits (e.g., Lang and Baker, 2001).

The sporadic outcrops within the project area mainly are altered volcanic rocks that were deposited at the time of the porphyry copper-gold mineralization and contain elevated potassium with respect to average values in other volcanic rocks in this province. Intrusive rocks within, or adjacent to, the project area include (1) an approximately 5 m-wide, porphyritic granodiorite dike that cuts the volcanic rocks within the project area, (2) a porphyritic intrusion that is exposed approximately 0.3 km to the east of the soil geochemical anomaly, and (3) a large, composite granitic to granodioritic body that likely solidified at the time of porphyry copper-gold mineralization and crops out approximately 0.8 km west of the boundary of the project area. Two fault zones, inferred from geophysical images, cut the granodioritic and volcanic rocks within the project area. A detailed aeromagnetic survey recorded an elliptical positive anomaly at the margins of the copper, gold and molybdenum geochemical soil anomalies. An inverted geophysical profile implies the presence of an ellipsoidal body approximately

100 m below the current surface. Taken as a whole, the geological, geochemical and geophysical data suggest that porphyry copper-gold mineralization may be present beneath the volcanic rocks at the prospect.

*Rationale for the assignment of probabilities*

The project area is located within a proven porphyry copper-gold province, close to economic porphyry systems, and next to a composite intrusion that was emplaced at the time of porphyry copper-gold mineralization. Hence, it is probable to highly probable that metals, ligands and fluids were extracted from appropriate sources (Table 1). Based on this prediction, a range of probability values from 0.90 to 0.98 (mean = 0.94) was assigned to $P_1$ (Fig. 2).

The estimated probability of ore components having migrated to a trap zone ($P_2$) is 0.56 (Fig. 2). This number is the product of the probability of emplacement of a finger-, sill-, or dike-like intrusion ($P_{2A}$ = 0.70; range: 0.60 to 0.80) and volatile exsolution ($P_{2B}$ = 0.80; range: 0.70 to 0.90). Evidence for $P_2$ includes (1) the presence of an elliptical geophysical anomaly that may be the signature of an intrusion underneath the volcanic rocks within the project area, (2) the presence of a porphyritic, dike-like intrusion, and (3) the presence of structures that are interpreted as having been active at the time of and exhibit a control on mineralisation.

A value of 0.49 was computed for the probability of trap formation ($P_3$ in Fig. 2). This value is the product of the probability of localized dilational deformation and creation of permeability focused on the target intrusion ($P_{3A}$) and the probability of the extent and intensity of the detected alteration assemblage being similar to that of economic porphyry deposits elsewhere in the region ($P_{3B}$). The value of $P_{3A}$ was estimated in the range from 0.60 to 0.80 (mean = 0.70), given the presence of composite igneous bodies and transcurrent fault zones within and adjacent to the project area, and thus a good chance that localized dilational deformation and creation of permeability were developed. The value of $P_{3B}$ was estimated in the range from 0.60 to 0.80 (mean = 0.70), given the presence of a large zone of intense potassium alteration similar to that of known economic porphyry copper-gold deposits in the area.

A value of 0.25 was calculated for the probability of metal deposition ($P_4$ in Fig. 2). This is the product of the probability that appropriate physico-chemical conditions for mineralization existed ($P_{4A}$), and the probability that the size of the trap and intensity of mineralization were sufficient to accumulate significant amounts of metal ($P_{4B}$). Elevated copper, gold, molybdenum, lead and zinc values at the prospect suggest that appropriate physico-chemical conditions for causing metal deposition existed within the project area. Hence, a range of probabilities from 0.4 to 0.6 (mean = 0.50) was assigned to $P_{4A}$. The value of $P_{4B}$ was also estimated in the range from 0.4 to 0.6 (mean = 0.50), given that the zones of anomalous copper, gold, molybdenum, lead and zinc in soils are large (800 × 600 m) and the coincident geophysical response is of a magnitude similar to that of the known economic porphyry copper-gold deposits in the belt. Therefore, the subjective probability of occurrence of a potentially economic porphyry copper-gold deposit at the prospect is:

$$\begin{aligned} P_{Mineralisation} &= P_1 \times (P_{2A} \times P_{2B}) \times (P_{3A} \times P_{3B}) \times (P_{4A} \times P_{4B}) \qquad (4) \\ &= 0.94 \times (0.70 \times 0.80) \times (0.70 \times 0.70) \times (0.50 \times 0.50) \\ &= 0.0645 \text{ or } 6.45\% \end{aligned}$$

Even in the case of an initial ore-grade drill intersection the project would still have to overcome two major hurdles prior to any decision to mine: a successful resource delineation programme and feasibility study. The conditional probability of delineating adequate resources given an initial ore-grade intersection is about 0.30 (range: 0.10 to 0.50); that of concluding a successful feasibility study is about 0.85 (range: 0.75 to 0.95) (P. Guj, unpublished data). When $P_{Mineralisation}$ is multiplied by 0.30 and 0.85 the product is 0.016 (1.6%). This number may seem small but it is significantly higher than or falls within the range of typical industry success (defined as the discovery of a mineral deposit that becomes a future mine) rates of 0.0003 to 0.005 for greenfields and 0.01 to 0.05 for brownfields exploration (e.g., Kreuzer, 2007).

### *Exploration cost and value distributions*

A first-pass program of 4 drill holes to depths of 300 m has been proposed to test this porphyry copper-gold target, which has never been drilled before. Given the uncertainty about the size and geometry of the target the exploration costs were estimated as the means of triangular distributions; the estimated minima and maxima are given in brackets. The expected (mean) cost of this program was estimated at $0.3 million (minimum cost: $0.1 million; maximum cost: $0.55 million). However, in the event that the drilling would intersect potentially economic porphyry copper-gold mineralization, additional, grid-based resource delineation drilling would have to follow. The most likely cost of this program is $4 million (minimum cost: $2 million; maximum cost: $5.5 million). If resource delineation is successful, the costs of a feasibility study are expected to add a further $10 million (minimum cost: $6.5 million; maximum cost: $14 million) to the exploration expenditure.

The possible value of the target distributes lognormally with an approximate mean of $248.2 million and standard deviation of $603.3 million. These parameters were obtained from fitting a lognormal distribution to the values of 33 porphyry copper deposits in the Metals Economic Group transactions database (Table 2). A minimum target value of $50 million was selected to reflect corporate financial objectives, the remote location of the project and other logistical considerations. The implication of this minimum target value is that a potential discovery with a value below $50 million would be sold rather than developed. Given that the largest known porphyry copper deposit in the region has an estimated value of approximately $1 billion, the lognormal distribution was truncated at this maximum value. As a consequence of the removal of all values less than $50 million and greater $1 billion a Monte Carlo simulation of this truncated distribution generates a mean ($143.457 million) and standard deviation ($193.448 million) that are somewhat lower than the respective values of the whole dataset.

As illustrated in Figure 4, the project owner has the option of terminating or selling the project given unsatisfactory results. Project termination in the absence of an initial ore-grade intersection is most likely to erode the value of the project to zero, whereas the options to sell the project are likely to create cashflows. For the purpose of this exercise these are estimated at $9.67 million (in the range from $5 to $14 million) given an initial ore-grade intersection, and $18.33 million (in the range from $5 to $30 million) and $8.00 million (in the range from $3 to $15 million) given that a resource delineation programme (e.g., deposit too small after resource delineation) or feasibility study (e.g., deposit subeconomic after feasibility) do not meet corporate targets.

### *Expected value (EV) calculation*

The EV (Appendix 1) of this porphyry copper-gold project was calculated using a decision tree (Fig. 4) constructed to suit the specific parameters of the project and illustrate uncertainties about the project geology and exploration expenditure linked to the decision by the company to drill the target. A Monte Carlo simulation produced a positively skewed distribution of possible project NPVs with a mean (expected) NPV of $2.628 million and standard deviation of $3.544 million. The minimum NPV of the project is -$0.122 million and linked to failure at the feasibility stage, whereas the maximum NPV is $27.201 million and linked to the possibility of a significant discovery. Based on the existing exploration results and supported by this analysis, the project was considered to offer acceptable risk-reward trade-offs and scheduled for initial drill testing.

## Discussion

### *Rationale and scope of the model and targeted user group*

The approach presented in this paper illustrates how to (1) translate mineral deposit models into flexible, probabilistic mineral systems models that are based on the critical processes of ore formation, (2) estimate and handle probability distribution functions of exploration costs and mineral deposit values, and (3) integrate these with basic risk analysis tools for calculating not only the EV of a particular project NPV, but also the probability distribution of all its possible NPV values surrounding it. This approach is more simplistic than those used by some major mineral resources companies (N. Hayward, BHP Billiton Ltd, pers. commun., 2006) but is highly appropriate for junior or intermediate companies that want to be more consistent and objective in evaluating and ranking their projects but have limited or no access to appropriate databases and/or specialists to develop, maintain and run sophisticated geological and financial risk and value models.

### *Problems in assigning subjective probabilities*

The companies with the best mineral deposit models and systems for controlling heuristic errors and biases (cf. McCuaig et al., 2007) have a competitive advantage when it comes to the reliability of their probability estimates.

Subjective probabilities assigned to geological risk factors are commonly over-optimistic or too inconsistent between projects (e.g., Rose, 1999) and biased given that geoscientists have to rely upon their previous experience when interpreting incomplete or inferior geoscientific datasets (e.g., Bond et al., 2007). Greater consistency and accuracy may be achieved by adopting disciplined interviewing techniques such as the Delphi technique (e.g., Rowe and Wright, 1999) and utilizing calibrated scales such as the Sherman-Kent scale (e.g., Jones and Hillis, 2003; Table 1). However, subjective probabilities should ideally be corroborated by objective frequency distributions of the outcomes of geological model studies of mineral deposits and actual mineral exploration projects.

More objective probabilities can also be derived from geological and spatial data analysis by methods such as logistic regression, weights of evidence, or artificial neural networks (e.g., Barnett and Williams, 2006). There is significant scope for exploring ways of linking mineral systems models to the Geographic Information System (GIS) and numerical modeling environments. Such an approach would generate more realistic data input for mineral systems models and allow testing multiple mineral deposit models and interpretations of the geology, structure and geochemical and geophysical surveys of a particular project area.

### *Problems in assigning probabilities when no information is available*

When operating under conditions of ignorance an analyst can only apply the same probability to mutually exclusive and collectively exhaustive possible events (Laplace criterion: e.g., Taha, 1976). Such an approach was adopted both in our model, and in the probabilistic approach of Lord et al. (2001), where a value of $P = 0.5$ indicates that there is an equal chance that a critical success factor did or did not operate when no information is available. However, it could be argued that we are never completely ignorant and that, given the low rate of occurrence of mineral deposits in individual exploration target areas, unfavorable evidence for critical subprocesses having occurred is statistically more likely to be present than favorable evidence. In other words, if we assume conditions of true ignorance, randomly choose a place on earth with no prior geological knowledge and assign $P = 0.5$ to all unknown risk factors (i.e., the critical sub-processes) in Figure 2 the resulting $P_{Mineralization}$ would be 0.008 or 0.8%. This figure is significantly greater than the chance of obtaining an initial ore-grade intersection for most early-stage projects generated by skilled exploration teams (N. Hayward, BHP Billiton Ltd, pers. commun., 2006). However, if we were to assign probabilities of less than 0.5 to risk factors in an area generated by a skilled exploration team but characterized by limited data (e.g., a part of a proven metallogenic province that is under cover) we would penalize this area compared to others where data are readily available. A serious consequence of this approach is that areas with high potential endowment but limited data may be rejected (cf. Hronsky and Groves, 2008).

### *Assumption of conditional independency*

For computational simplicity the probabilistic approach of Lord et al. (2001) assumed that the critical success factors of ore formation ($P_1$ = ore component sources, $P_2$ = fluid conduits, $P_3$ = trap sites, and $P_4$ = physico-chemical processes at the trap sites) are conditionally independent. In reality some of these process factors may not necessarily be independent. For example, the trap site ($P_3$) of a lode-gold deposit may constitute a small part and be a subsidiary fault geometry of the fault zone that acted as the fluid conduit ($P_2$). Furthermore, research by workers such as Cox et al. (2001) and Sibson (1990) illustrates that the best fluid conduits have only local dilations under weak bulk strain conditions, favoring the greatest fluid flux. Such settings are intimately associated with supralithostatic fluid overpressure and hydrofracturing of less permeable subsidiary structures to create fertile traps sites. These catastrophic fault-valve fluid releases require a strong dependence between fluid conduits and trap sites. Ignoring dependencies between different process elements can bias $P_{Mineralization}$ and thus the outcome of the modeling.

Additional work is required to identify and quantify interdependencies and their impact on the models. Possible solutions may lie in (1) the application of a conditional Bayesian (Appendix 1) rather than multiplicative approach as proposed by Lord et al. (2001), (2) numerical modeling of the processes that represent the critical first-order controls on the mineral system of interest (e.g., Potma et al., 2008), and/or (3) breaking down mineral systems into their fundamental, independent physico-chemical factors that cause ore deposition (i.e., permeability, gradient in non-hydrostatic fluid pressure, solubility sensitivities, spatial gradients in temperature, pressure and concentration of metal species, and the duration of the system) (Barnicoat et al., 2007).

## Summary and Conclusions

The probabilistic mineral systems model introduced in this paper is a flexible, internally consistent template that is structured in accordance with the previously published, and widely accepted petroleum and mineral systems approaches.

The model integrates the critical processes of ore formation and scale and intensity of metal deposition with basic concepts of probability theory and financial and decision analysis, thereby generating a link between the geological potential of an exploration project and its probability-adjusted financial value. As such, the probabilistic mineral systems model provides a powerful tool for (1) assessing the probability of exploration success, (2) ranking and evaluating exploration opportunities on a uniform and consistent basis, (3) planning exploration programs on a basis of probability-based expected values (EVs), (4) predicting possible outcomes and selecting the most financially advantageous course of action under conditions of uncertainty, and (5) highlighting what additional types of geological information could be collected for improving the chance of success and achieving greater EV.

A real-world case study illustrates how the probabilistic mineral systems model can generate a measure of the probability of ore formation and how this probability can be used in an exploration decision tree that incorporates Monte Carlo simulation capability. This tree is intended for calculating the expected (mean) net present value (NPV) of an exploration project under deterministic conditions and then, by means of Monte Carlo simulation, the variability of all possible NPVs surrounding the EV within a minimum and maximum range and their probability distribution.

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## Appendix 1: Background to Quantitative Methods

*Basic concepts of probability theory*

A probability is a numerical measure of the likelihood that a particular chance outcome will occur. Given that any outcome has no more than a 100 per cent and no less than a zero per cent chance of occurrence, probabilities are assigned on a scale from zero to one. Translated into an exploration scenario, a probability of occurrence of a particular ore-forming process of $P = 1.0$ can be assigned only where drilling or other hard data prove that the process operated. A probability of $P = 0.0$ denotes that the critical process definitely did not operate. A value of $P = 0.5$ means that it is equally likely that a critical process did or did not operate within a skillfully selected project area (Lord et al., 2001).

There are two ways of obtaining probabilities: theoretically and empirically. Theoretical probabilities are those that can be determined by rigorous mathematical calculations or purely objective logic, and thus are independent of prior experience. Determination of theoretical probabilities requires complete understanding of a system (e.g., card or roulette game). Empirical probabilities, on the other hand, are estimates of the relative frequency of events, based on past observations, experimental trials and experience ranging from relatively objective to subjective. Objective empirical probabilities are those that rely on quantitative historical information from identical or comparable situations, whereas subjective probabilities reflect a person's (or group's) degree of belief that a particular outcome will occur. Although subjective, these estimates are indispensable in situations where empirical data are not available or meaningless. Probability judgments in mineral exploration generally fall in the subjective empirical category.

Chance events are said to be mutually exclusive if their occurrence excludes or precludes the occurrence of any other possible event. Chance events are collectively exhaustive when they contain all possible outcomes of an experiment. Probability theory dictates that a set of individual, mutually exclusive and collectively exhaustive chance events must add up to one. When two or more events are independent, the probability that all the outcomes will occur simultaneously (jointly or in sequence) is the product of the individual probabilities of occurrence (e.g., Lapin, 1994; Everitt, 1999; Newendorp and Schuyler, 2000; Wisniewski, 2002; Morris, 2003):

$$P(A + B + C + D) = P_A \times P_B \times P_C \times P_D \qquad (1).$$

The underlying assumption of the application of this multiplication rule to the probabilistic analysis of ore-forming processes (e.g., Lord et al., 2001) is that the occurrence of one critical process of ore formation in no way affects, or is affected by, the occurrence of the other critical processes.

### *Bayesian (conditional) probability*

Bayes’ rule (also known as Bayes’ theorem) provides a theoretical framework for revision or updating of an initial (prior) belief about the likelihood of an event (event A) before its outcome, or the outcome of a second event (event B) is observed. This prior distribution is the probability distribution before knowing the outcome of A or B. After having observed A or B, we update our judgment. The new posterior probability distribution can be calculated using Bayes' rule. The posterior probability is conditional and written as $P(A|B)$ = probability of A given B (e.g., Lapin, 1994; Newendorp and Schuyler, 2000; Murtha, 2000; Albert and Rossman, 2001; Petrie et al., 2003).

As an example, without information about the prior probability of occurrence of a mineral deposit at a particular location, it is impossible to determine the posterior probability of such an occurrence given a range of exploration data. It is the posterior probability on which we base our key exploration decisions (e.g., drill or collect more data, abandon or stay), whether we do it explicitly or, more commonly, implicitly by combining personal judgment, experience, intuition and a variety of target ranking schemes. The following example may serve to illustrate how Bayes' rule was built into the probabilistic mineral systems model for calculating the probability that a mineral deposit occurs at a particular location given the result of an additional targeting technique relating to that location (cf. Barnett and Williams, 2006). Mathematically this problem can be expressed as:

$$P(D \mid A) = \frac{P(D) \times P(A \mid D)}{P(D) \times P(A \mid D) + P(D') \times P(A \mid D')} \tag{2}$$

where $P(D)$ = prior probability of occurrence of a mineral deposit at a particular location, $1 - P(D) = P(D') =$ complementary event of $P(D)$ or the prior probability of failure, $P(A|D)$ = conditional probability of an anomaly given the presence of a mineral deposit or the true positive rate of the targeting tool, $P(A|D')$ = conditional probability of an anomaly given that no mineral deposit is present or the false positive rate of the targeting tool (e.g., Lapin, 1994; Newendorp and Schuyler, 2000; Murtha, 2000; Albert and Rossman, 2001; Petrie et al., 2003).

*Expected value (EV) concept*

The EV concept is the probability-weighted, or mean, value of all possible outcomes of an investment decision. The merit of this concept lies in its explicit incorporation of uncertainty into a future value estimate. As such, the EV concept is a decision-making tool that facilitates project ranking when companies are risk-neutral. Risk-neutral investors maximize EV and are indifferent to the magnitude of potential losses. However, in reality most investors are risk-averse. Decision alternatives with positive EVs are considered investments; those with negative EVs are gambles (e.g., e.g., Drew, 1972; Rose, 1999; Newendorp and Schuyler, 2000; Lord et al., 2001). The EV equation is defined as:

$$EV = V_1 \times P(V_1) + V_2 \times P(V_2) + ... + V_N \times P(V_N) = \sum_{i=1}^{N} V_i \times P(V_i) \qquad (3)$$

where $EV$ = expected (mean) value of the investment, $V$ = value of individual possible discrete outcomes (net present value (NPV) of target at decision-to-mine, or any other agreed measure of monetary value), $P(V)$ = probability of $V$ occurring, $N$ = number of possible outcomes, and $i$ = outcome 1, 2, 3, … , $k$ (e.g., Newendorp and Schuyler, 2000).

## Appendix 2: Examples of Mineral Systems Models

Models were formulated for lode-gold, porphyry-copper, nickel-sulfide and stratiform lead-zinc deposits, to develop and test the application of the probabilistic mineral systems model. They are presented here as examples of how to assign critical processes of ore formation to the model template.

### *Lode-gold systems model*

Lode-gold deposits are rare but reproducible products of tectonothermal anomalies that were created during the evolution of convergent plate margins by accretionary and collisional processes (e.g., Kerrich and Cassidy, 1994; Hagemann and Cassidy, 2000; Goldfarb et al., 2001a, b; Groves et al., 2003; Groves et al., 2005). Isotopic tracers of fluid sources have not provided definite evidence of the origin of the ore components (e.g., Ridley and Diamond, 2000), but it is most likely that they were sourced from rocks or melts, or both, present in convergent plate margin environments. Commonly cited models for extraction of ore components from their sources include mantle degassing (e.g., McCuaig and Kerrich, 1998) and deep penetration and circulation of meteoric waters (e.g. Neng et al., 1999; Yao et al., 1999; Mishra and Panigrahi, 1999; Boiron et al., 2003; Vallance et al., 2003, 2004), although Ridley and Diamond (2000) suggested that only the concepts of magmatic and metamorphic devolatilization have held up to scientific scrutiny and testing.

Transport of large quantities of ore components from source to trap regions can only occur and be sustained where fluids have access to permeable pathways. Such conduits may include aquifers but are commonly fault or shear zones that are being actively deformed. However, permeability can be rapidly destroyed by such processes as fracture sealing during mineral deposition. Hence, deformation must be ongoing for structures to be continuously or repeatedly active and to maintain their effectiveness of passing the enormous volumes of fluid and metals required to produce a sizeable gold deposit (e.g., Sibson, 1990; Cox, 1999; Cox et al., 2001).

According to Cox et al. (2001), fluid flow within fault and shear zones is controlled by fracture aperture and fracture density, and thus the degree of permeability. Permeability depends to some extent on rock type but is principally localized by fault irregularities, such as jogs, steps, bends and splays. These damage zones form very effective, narrow fluid channels that may act as metal traps where their active deformation coincides in space and time with processes that are capable of destabilizing the physical and chemical balance of the ore-forming fluids. Alternatively, a metal trap may form where relatively soluble rocks, such as dolomite or limestone, are locally dissolved by ore-forming fluids as envisaged for Carlin-type gold deposits (e.g., Emsbo et al., 2003). Given that great volumes of fluid and high fluid flux are needed for transporting to the trap zone the volume of metal that is contained within a large gold deposit (e.g., Cox et al., 1991), a trap should generally be characterized by wall-rock alteration of much greater three-dimensional extent and intensity than that in areas away from the trap.

Important and widely accepted processes of metal deposition within lode-gold environments include (1) adiabatic and conductive cooling of ore-forming fluids, (2) interaction between ore-forming fluids and their wall rocks, (3) phase separation as a reaction to pressure decrease at the time of ascent or throttling of ore-forming fluids, and (4) the mixing of two or more fluids with different physical and chemical properties (e.g., McCuaig and Kerrich, 1998; Mikucki, 1998). For metal deposition to occur, these processes have to operate at trap sites on fault or shear zones that are being deformed repeatedly or continuously at the time of activity of the gold-related hydrothermal system. Regardless of the type of physico-chemical process that triggered metal deposition, the three-dimensional extent of a trap must be large enough to host a sizeable and economic mineral deposit.

### *Porphyry-copper systems model*

Porphyry-copper (± gold, ± molybdenum) deposits are products of subduction-related magmatism at convergent plate margins (e.g., Sillitoe, 2000; Richards, 2003; Cooke et al., 2005). Sillitoe (2000), Richards (2003), Hollings et al. (2004), White (2004) and Cooke et al. (2005) suggest that most giant porphyry-copper deposits, particularly those that are <20 m.y. old, formed in regions where there have been (1) low angle subduction of thicker than average oceanic crust (e.g., aseismic ridges, oceanic plateaus or seamount chains), (2) changes in the dip of the subduction zone that resulted in tearing or bending of the slab, (3) changes from orthogonal to oblique subduction; (4) reversals of arc polarity, or (5) collisional events that resulted in crustal thickening, rapid uplift, exhumation and generation of oxidized melts capable of transporting copper, gold and sulfur dioxide.

Magma ascent is regarded by many authors as a process that is controlled by structures that are actively being deformed (e.g., Tosdal and Richards, 2001; Chernicoff et al., 2002; Richards, 2003), whereas others (e.g., Paterson and Schmidt, 1999, 2001; Sillitoe, 2000) suggest that melt transport and emplacement are neither focused nor channeled by faults. In the porphyry-copper model, it is crucial that magma ascent and emplacement result in the formation of finger-, sill- or dike-like intrusions that, as indicated by empirical data, are mainly found in areas of dilation at or near regional-scale fault zones (e.g., Lindsay et al., 1995; Garwin, 2002; Richards, 2003; Guillou-Frottier and Burov, 2003). Additional critical process steps in the migration of ore components to trap regions are exsolution of volatiles from the melt (first boiling) and water saturation of the melt caused by the crystallization of anhydrous phases (second boiling), controlled by cooling and crystallization of the melt, deformation of the roof rocks and volume expansion (i.e., decompression) of the ore-forming fluids. The prefixes ‘first’ and ‘second’ are not indicative of the order of the boiling events as both processes occur repeatedly over the time of formation of a porphyry-copper deposit (e.g., Cline, 2003).

Most porphyry-copper deposits are hosted, either fully or partially, by finger-, sill- or dike-like intrusions of composite porphyry stocks (e.g., Sillitoe, 2000), implying that dilational deformation, permeability and fluid flux were mainly focused on the mineralized subvolcanic centers (e.g., Lindsay et al., 1995). Recurring fracturing events created damage zones of high permeability (e.g., up to 50 fractures per meter at Batu Hijau: Garwin, 2002) that served as effective trap zones. The great three-dimensional extent, intensity and degree of overprinting (telescoping) of hydrothermal alteration zones centered on porphyry-copper deposits further suggests that by far the greatest volume of hot, acidic fluid was channeled through these locations (e.g., Garwin, 2002).

Metal deposition from ore-forming fluids within porphyry-copper environments is commonly brought about by phase separation, migration down temperature and pressure gradients, fluid-rock interaction and mixing with external fluids (e.g., Richards, 2003). For an economic porphyry-copper deposit to be formed, the trap region has to be capable of holding large volumes of metals in closely spaced veins or large breccia bodies. Giant porphyry-copper deposits, such as Batu Hijau and Chuquicamata, also show evidence for recurring fracturing events as practically all fractures were opened and mineralized more than once (Lindsay et al., 1995; Ossandon et al., 2001; Garwin, 2002).

### *Magmatic nickel-sulfide systems model*

Magmatic nickel-copper (± cobalt, ± platinum group metals) deposits are restricted to mafic to ultramafic, olivine-rich intrusions, commonly forming part of large igneous provinces. The origin of these complexes has been linked to either melting of mantle sources within hot regions (“hot spots”) in the mantle or arrival of mantle plumes at the base to the source regions. Commonly proposed tectonic environments are intracontinental rift and rifted continental margin settings (e.g., Naldrett, 1989, 1992; Wooden et al., 1992; Misra, 2000; Li et al., 2001; Jaques et al., 2002; Diakov et al., 2002; Yakubchuk and Nikishin, 2004; Lesher, 2004).

Contamination of magmas with crustal sulfur as they migrate from source to trap regions or magma mixing, or both, or fractional crystallization in staging chambers are considered by most workers as essential for achieving sulfur saturation of the melts (e.g., Naldrett, 1992; Chai and Naldrett, 1992; Li and Naldrett, 2000; Li et al., 2001, 2002; Hannah and Stein, 2002; Arndt et al., 2003).

A number of studies have illustrated that massive sulfide ores at Noril’sk (Naldrett et al., 1996), Voisey’s Bay (Evans-Lamswood et al., 2000) and Uitkomst (Li et al., 2002) accumulated at specific sites within the magma conduits (dynamic environments), whereas the sulfide content of rocks comprising the magma chambers (low-energy environments) is commonly much lower. Based on this concept, Evans-Lamswood et al. (2000) and Diakov et al. (2002) developed predictive models, suggesting that metals in nickel-sulfide systems are most likely to be trapped at sites where changes to conduit morphology affect the magma flow regime (e.g., decrease or increase of conduit width, change in conduit orientation, entry points to magma chambers, structural discontinuities, localized stoping and thermal erosion). In some nickel-sulfide systems, metal concentration was clearly controlled by localized dilational deformation, permeability and decompression. An excellent example is the Jinchuan deposit, where discontinuous fracture zones within the nickel ore are rich in platinum group metals (e.g., up to 2.4 ppm Pt: Chai and Naldrett, 1992). As illustrated by intrusions in the Noril’sk region, metasomatic zones around mineralized igneous bodies are everywhere of higher temperature origin and spatially more extensive than those surrounding barren plutons. In addition, the metasomatic zones around mineralized intrusions are everywhere thicker than the intrusions themselves (Diakov et al., 2002).

Metal deposition within trap zones is controlled by three critical subprocesses: (1) the mafic to ultramafic magma has to reach the point of sulfur saturation for segregation of liquid sulfide droplets to occur, (2) the liquid sulfide has to interact with sufficient volumes of new magma to concentrate chalcophile metals at the trap site to an economic level, and (3) for an economic deposit to form, the liquid sulfides have to be concentrated within a relatively small volume of rock (e.g., Naldrett, 1989; Hannah and Stein, 2002).

### *Stratiform zinc-lead systems model*

Sedimentary-hosted exhalative- (SEDEX) and Irish-type stratiform zinc-lead (± silver, ± barite) deposits are located within extensive, long-lived rift-sag basins in which clastic and volcanic rocks dominate the rift phase and shales and carbonates dominate the sag phase. They are interpreted to have formed in rifted continental margin, intracontinental or back-arc settings (e.g., McGoldrick and Large, 1998; Large et al., 2002; Betts et al., 2003). Metals contained in these deposits were extracted by evolved basinal brines from either intra- (volcanic and volcanoclastic rocks, sandstone) or extrabasinal (basement) sources (e.g., Johnston, 1999; Leach et al., 2004).

Transport of ore components from source to trap regions was most likely achieved by topography-driven and/or convective migration of basinal brines through aquifers or along regional-scale, basin-penetrating structures (i.e., dilatant fault segments, fault intersections) that were being actively deformed (e.g., Johnston, 1999; Garven et al., 2001; Large et al., 2002; Betts and Lister, 2002).

Four fundamentally different models have been proposed for the formation of trap zones in stratiform zinc-lead systems: (1) localized rock dissolution and replacement (e.g., Wilkinson et al., 2005); (2) replacement of undercompacted shale horizons or petroleum accumulations (e.g., Broadbent et al., 1998; Broadbent et al., 2002; Ord et al., 2002); (3) localized dilational deformation, permeability and fluid flux (e.g., Johnston, 1999); (4) fluid pooling in sea-floor depressions next to or near regional-scale fault zones (e.g., Goodfellow et al., 1993; Cooke et al., 2000; Sangster, 2002). Alteration zones associated with giant or larger stratiform zinc-lead deposits are everywhere of great extent and intensity (e.g., Large et al., 2002).

According to Cooke et al. (2000) and Large et al. (2002), metal deposition from oxidized brines requires a separate source of reduced sulfur to mix with the ore-forming brine, or a mechanism for generating reduced sulfur at the site of metal deposition. These processes can be achieved by interaction of ore-forming brines with carbon-rich rocks or fluids, such as those of anoxic brine pools or hydrocarbon reservoirs. Metal precipitation from reduced brines can be triggered by processes, such as cooling, pH increase or addition of reduced sulfur. These processes may result from mixing of the reduced brines with seawater or interaction with carbonate-rich wall rocks (e.g., Cooke et al., 2000; Large et al., 2002). Thus, large replenishable reservoirs are required for the accumulation of huge volumes of zinc, lead and silver. In addition, host rock sequences (or brine pools) have to be of great lateral extent and continuity, and prospective host rock packages of great thickness (e.g., Rohrlach et al., 1998; Betts and Lister, 2002).

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## Figure Captions

**Fig. 1.** Schematic overview of the modeling process: **(A)** a subjective (expert) measure of the probability of ore occurrence computed in the probabilistic mineral systems model for a particular project area or target and **(B)** estimates of the costs of mineral exploration and feasibility, and the possible value of the targeted mineral deposit style serve as inputs for **(C)** an exploration decision tree that offers possible decision alternatives. **(D)** Monte Carlo simulation of the exploration decision tree produces **(E)** the expected value (EV) of a particular exploration project and the probability distribution of all its possible NPVs within a minimum and maximum range.

**Fig. 2.** Excel™-integrated probabilistic mineral systems model for porphyry-copper (± gold, ± molybdenum) deposits. Discrete probabilistic values (on a scale from 0.0 to 1.0) or ranges of likely values as illustrated in this example are assigned to each critical subprocess. Each assignment must be based on geological evidence for the particular subprocess having operated at the location of interest. The probability of occurrence of a critical process is the product of the probabilities assigned to the each critical subprocess. By multiplying $P_1$, $P_2$, $P_3$ and $P_4$, a probability of occurrence of potentially economic mineralization ($P_{Mineralization}$) can be obtained for a particular area of interest (cf. Lord et al., 2001). Where a range of probabilities is assigned, the values are assigned a uniform distribution that is characterized by the minimum and maximum of the range and constant probability.

**Fig. 3.** Exploration decision tree offering three main decision paths: (1) drill, (2) apply additional targeting technique, and (3) terminate. The tree can be used in either a deterministic or probabilistic manner. The deterministic tree (illustrated in this figure) is intended to calculate the "base case" expected value (EV) of a project for which drillable targets have been or are being identified (i.e., exploration stage B of Lord et al., 2001) and as a function of expected (mean) values of inputs. The probabilistic tree integrates the probabilistic distributions of the inputs outlined in Figure 1A and B with a Monte Carlo simulation tool for computing not only the EV of a project but also the probability distribution of all possible project NPVs within a minimum and maximum range. Key to abbreviations: EV = expected value; $M = million dollars.

**Fig. 4. (A)** Schematic representation of the exploration decision tree and probabilistic cost and value distributions as applied to a real-world porphyry copper-gold case study (see text for details). The case study illustrates how the probabilistic mineral systems model can generate a measure of the probability of ore formation and how this probability can be used in an exploration decision tree that incorporates Monte Carlo simulation capability. **(B)** Results of the simulation of the distribution of all possible net present values (NPVs) of the drill decision. **(C)** Results of the simulation of the distribution of all possible values of the porphyry-copper target sampled in the range from $50 million to $1 billion. Key to abbreviations: $M = million dollars.

**Appendix 2, Fig. 1.** Mineral systems model template for lode-gold deposits (see text for a rationale for the formulation of the geological process model). The model sheets consist of five parts: (1) the essential elements of the mineral system; (2) the critical processes and subprocesses that must operate for ore deposition to occur within a particular area; (3) the four-dimensional extent of the ore-forming system; (4) post-ore processes such as outflow of spent fluids from trap zones, upgrading of mineral systems by supergene or metamorphic processes, and preservation of mineral systems through time; and (5) decision-making (i.e., to drill test, seek further information via an additional targeting technique, or abandon a project).

**Appendix 2, Fig. 2.** Mineral systems model template for porphyry-copper (± gold, ± molybdenum) deposits.

**Appendix 2, Fig. 3.** Mineral systems model template for magmatic nickel-sulfide (copper, ± cobalt, ± platinum group metals) deposits.

**Appendix 2, Fig. 4.** Mineral systems model template for stratiform zinc-lead (± silver, ± barite) deposits.

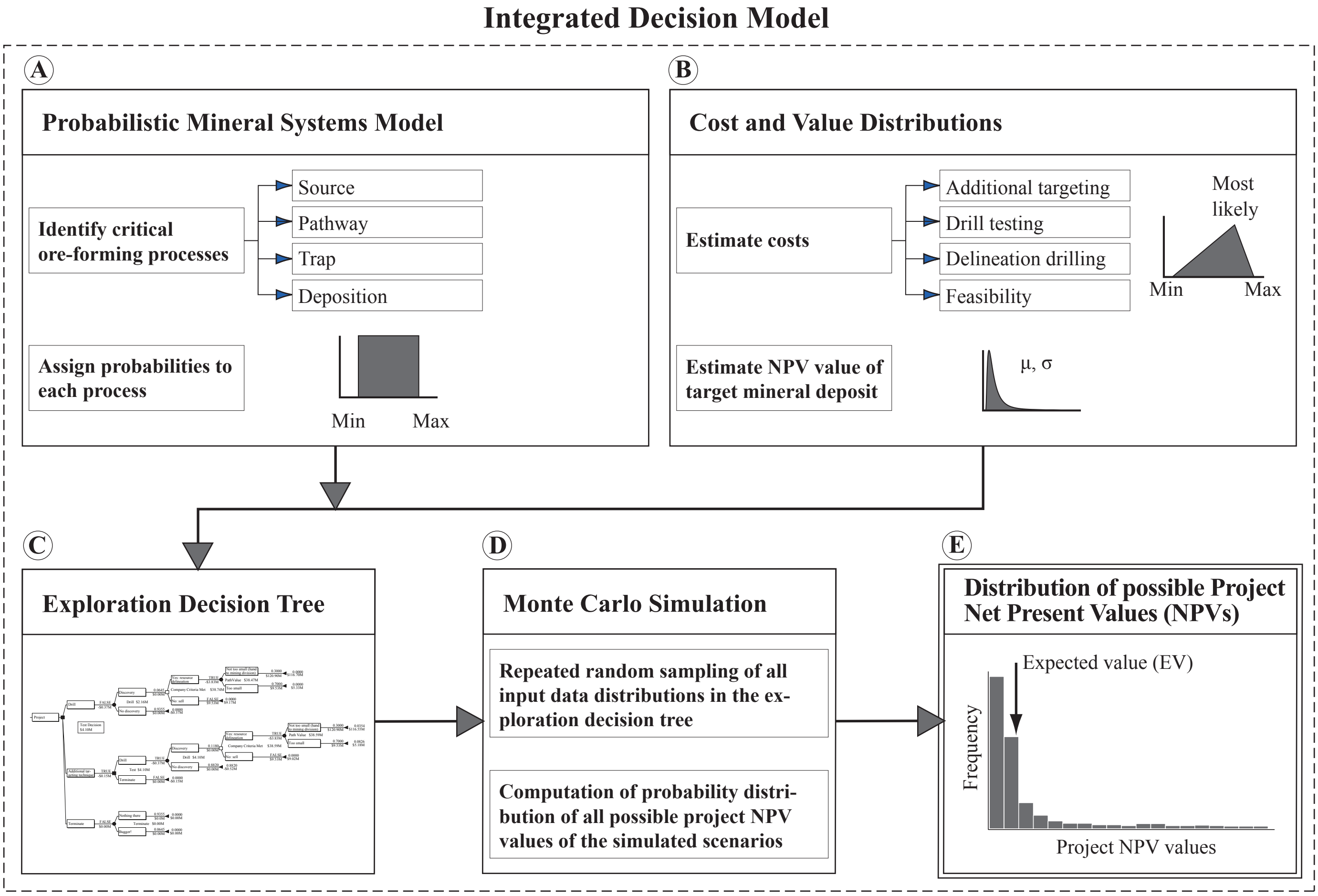

Integrated Decision Model
A
Probabilistic Mineral Systems Model
Identify critical ore-forming processes
Source
Pathway
Trap
Deposition
Assign probabilities to each process
Min
Max
B
Cost and Value Distributions
Estimate costs
Additional targeting
Drill testing
Delineation drilling
Feasibility
Most likely
Min
Max
Estimate NPV value of target mineral deposit
μ, σ
C
Exploration Decision Tree
D
Monte Carlo Simulation
Repeated random sampling of all input data distributions in the exploration decision tree
Computation of probability distribution of all possible project NPV values of the simulated scenarios
E
Distribution of possible Project Net Present Values (NPVs)
Expected value (EV)
Frequency
Project NPV values

Figure 1.

| Critical Processes: | | Critical Subprocesses: | Min: | Max: | Mean: | Evidence for Process and Subprocess Occurrence, e.g.: |
|---|---|---|---|---|---|---|
| Extraction from Sources<br>**P$_1$ =** **0.940** | **P$_1$** | Melting at convergent plate margin? | 0.900 | 0.980 | **0.940** | Appropriate geographic, stratigraphic and temporal setting (i.e. four-dimensional extent)?<br>Mappable evidence for fluid sources (magmatic, meteoric)?<br>Mappable evidence for ligand sources (magma, host rock, basement)?<br>Mappable evidence for metal sources (magma, host rock, basement)?<br>Mappable evidence for energy sources (e.g., tectono-thermal anomaly)? |
| Migration to Trap<br>**P$_2$ =** **0.560** | **P$_{2A}$** | Emplacement of finger-, sill-, or dyke-like intrusions? | 0.600 | 0.800 | **0.700** | Intrusion age, geometry, mineralogy, texture and composition?<br>Are they part of composite, compositionally heterogeneous stocks?<br>Geophysical evidence for the deeper-level magma chambers?<br>District structure and structural controls, and strain field at the time of emplacement?<br>Province fertility (copper, gold and / or molybdenum occurrences / deposits)? |
| | **P$_{2B}$** | Volatile exsolution (first and second boiling)? | 0.700 | 0.900 | **0.800** | |
| Formation of Trap<br>**P$_3$ =** **0.490** | **P$_{3A}$** | Dilational deformation, permeability and fluid flux focused on intrusion? | 0.600 | 0.800 | **0.700** | Local structure and structural controls?<br>Local strain field at the time of volatile exsolution?<br>Alteration assemblages, zoning and overprinting?<br>Mappable extent of alteration assemblages? |
| | **P$_{3B}$** | Great extent and intensity of alteration? | 0.600 | 0.800 | **0.700** | |
| Deposition of Metal<br>**P$_4$ =** **0.250** | **P$_{4A}$** | Fluid mixing, fluid-rock interaction, boiling or cooling and pressure decrease? | 0.400 | 0.600 | **0.500** | Apropriate fluid types and chemistry?<br>Geometry, size and continuity of trap zone?<br>Physical parameters of trap zone?<br>Modelling results?<br>Evidence for multiple episodes of breccia and / or vein formation? |
| | **P$_{4B}$** | Great volume of open space and multiple generations of breccia or veins? | 0.400 | 0.600 | **0.500** | |

**$P_{Mineralization}$ = 0.064**

**Figure 2.**

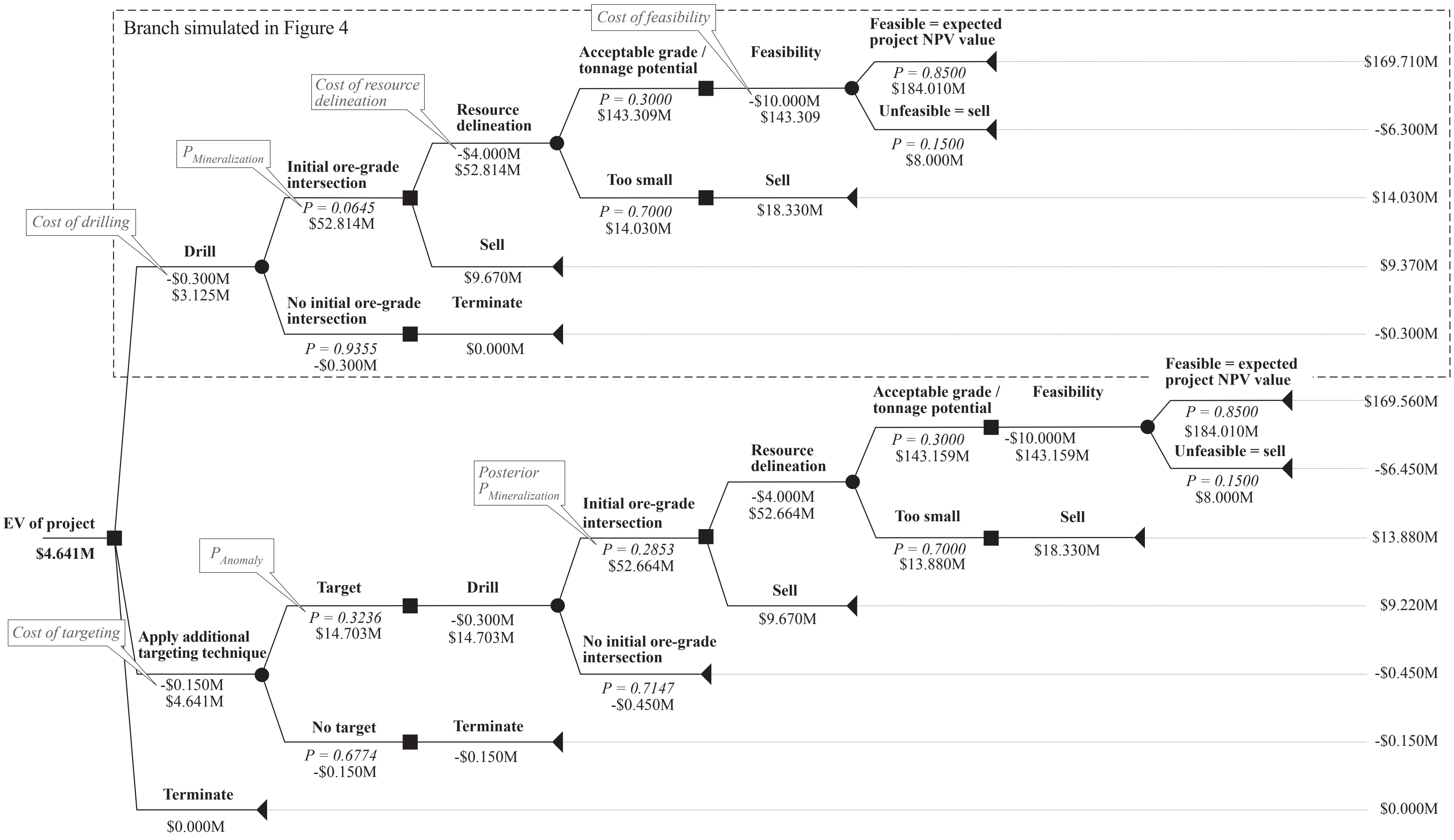
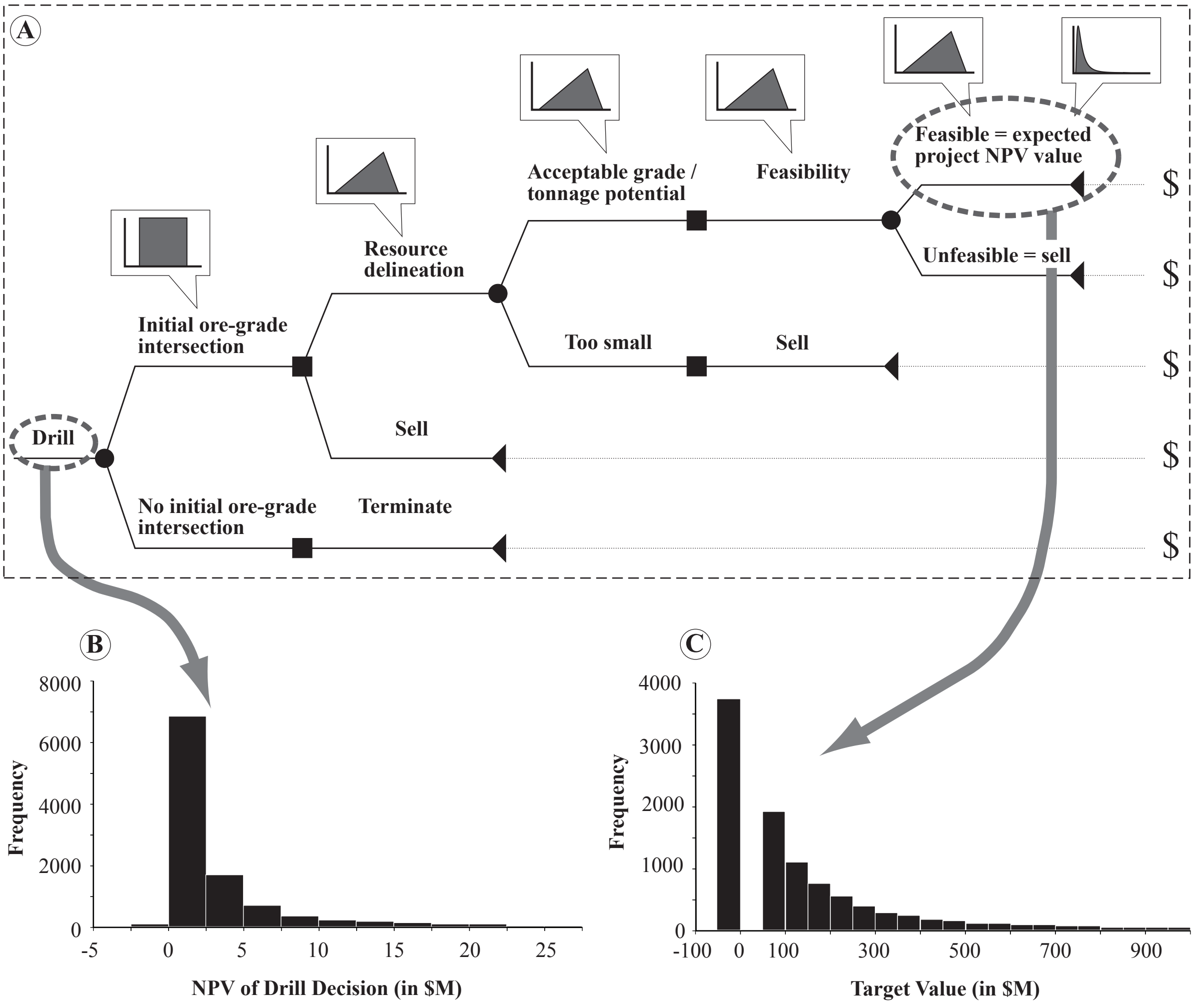

Branch simulated in Figure 4
Cost of feasibility
Feasible = expected project NPV value
Acceptable grade / tonnage potential
Feasibility
$169.710M
Cost of resource delineation
P = 0.3000
$143.309M
-$10.000M
$143.309
P = 0.8500
$184.010M
Resource delineation
Unfeasible = sell
-$6.300M
P = 0.1500
$8.000M
P Mineralization
Initial ore-grade intersection
-$4.000M
$52.814M
Too small
Sell
P = 0.0645
$52.814M
P = 0.7000
$14.030M
$18.330M
$14.030M
Cost of drilling
Sell
Drill
$9.670M
$9.370M
-$0.300M
$3.125M
No initial ore-grade intersection
Terminate
P = 0.9355
-$0.300M
$0.000M
-$0.300M
Feasible = expected project NPV value
Acceptable grade / tonnage potential
Feasibility
$169.560M
P = 0.3000
$143.159M
-$10.000M
$143.159M
P = 0.8500
$184.010M
Unfeasible = sell
-$6.450M
Posterior P Mineralization
Resource delineation
P = 0.1500
$8.000M
-$4.000M
$52.664M
Initial ore-grade intersection
EV of project
$4.641M
Too small
Sell
P = 0.2853
$52.664M
P = 0.7000
$13.880M
$18.330M
$13.880M
P Anomaly
Target
Drill
Sell
P = 0.3236
$14.703M
-$0.300M
$14.703M
$9.670M
$9.220M
Cost of targeting
Apply additional targeting technique
-$0.150M
$4.641M
No initial ore-grade intersection
P = 0.7147
-$0.450M
-$0.450M
No target
Terminate
P = 0.6774
-$0.150M
-$0.150M
-$0.150M
Terminate
$0.000M
$0.000M

Figure 3.



| | |
|---|---|
| Mean (= EV) | $2.628M |
| Standard deviation | $3.544M |
| Minimum | -$0.122M |
| Median | $1.352M |
| Maximum | $27.201M |

| | |
|---|---|
| Mean (= EV) | $143.457M |
| Standard deviation | $193.000M |
| Minimum | $0.000M |
| Median | $79.000M |
| Maximum | $999.999M |

Figure 4.

**Table 1. Sherman-Kent Scale for Quantifying Subjective Probability Estimates (modified from Jones and Hillis, 2003)**

| Numerical Value | Corresponding Verbal Prediction |
|---|---|
| 0.98–1.00 | Proven; definitely true |
| 0.90–0.98 | Virtually certain; convinced |
| 0.75–0.90 | Highly probable; strongly believe; highly likely |
| 0.60–0.75 | Likely; probably true; about twice as likely to be true as untrue; chances are good |
| 0.40–0.60 | Chances are about even, or slightly better than even or slightly less than even |
| 0.20–0.40 | Could be true but more probably not; unlikely; chances are fairly poor; two or three times more likely to be untrue than true |
| 0.02–0.20 | Possible but very doubtful; only a slight chance; very unlikely indeed; very improbable |
| 0.00–0.02 | Proven untrue; impossible |

**Table 2. Databases of the value of mineral deposits**

| Database | Period | Entries | Source | Characteristics | Valuation Method | Currency | Parameters | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | μ | σ |
| Gold and Base Metals Acquisitions | 1993–2003 | 343 | Metals Economics Group | Large global dataset<br>Broad spectrum of deposit styles<br>Broad range of commodity types<br>Broad spectrum of pre-mining projects at various stages of exploration | Project transaction prices in dollars of the day | 2004 A$[1] | 121.09 | 303.95 |
| Australian Gold Discoveries | 1985–2002 | 59 | Schodde (2003) | Small Australian dataset<br>Norrow range of gold deposit syles<br>Restricted commodity spectrum (gold ± copper)<br>Restricted to projects that were actually mined<br>Coherent data based on a single study<br>Robust methodology of compilation | NPV calculations based at the time of decision to mine, using constant A$550/oz and the tax rules of today | 2003 A$ | 85.85 | 193.12 |
| Global Copper Projects | 1992–2004 | 65 | Leveille and Doggett (2006) | Small global dataset<br>Various copper deposit syles<br>Restricted commodity spectrum (copper, gold, silver, molybdenum, zinc, cobalt)<br>Restricted to projects that were actually mined<br>Coherent data based on a single study<br>Robust methodology of compilation | IRR and NPV calculations at discount rates of 8%, based on an effective tax rate of 30% and average metal prices over the period 1992-2004 | 2004 US$ | 285.51 | 1748.80 |

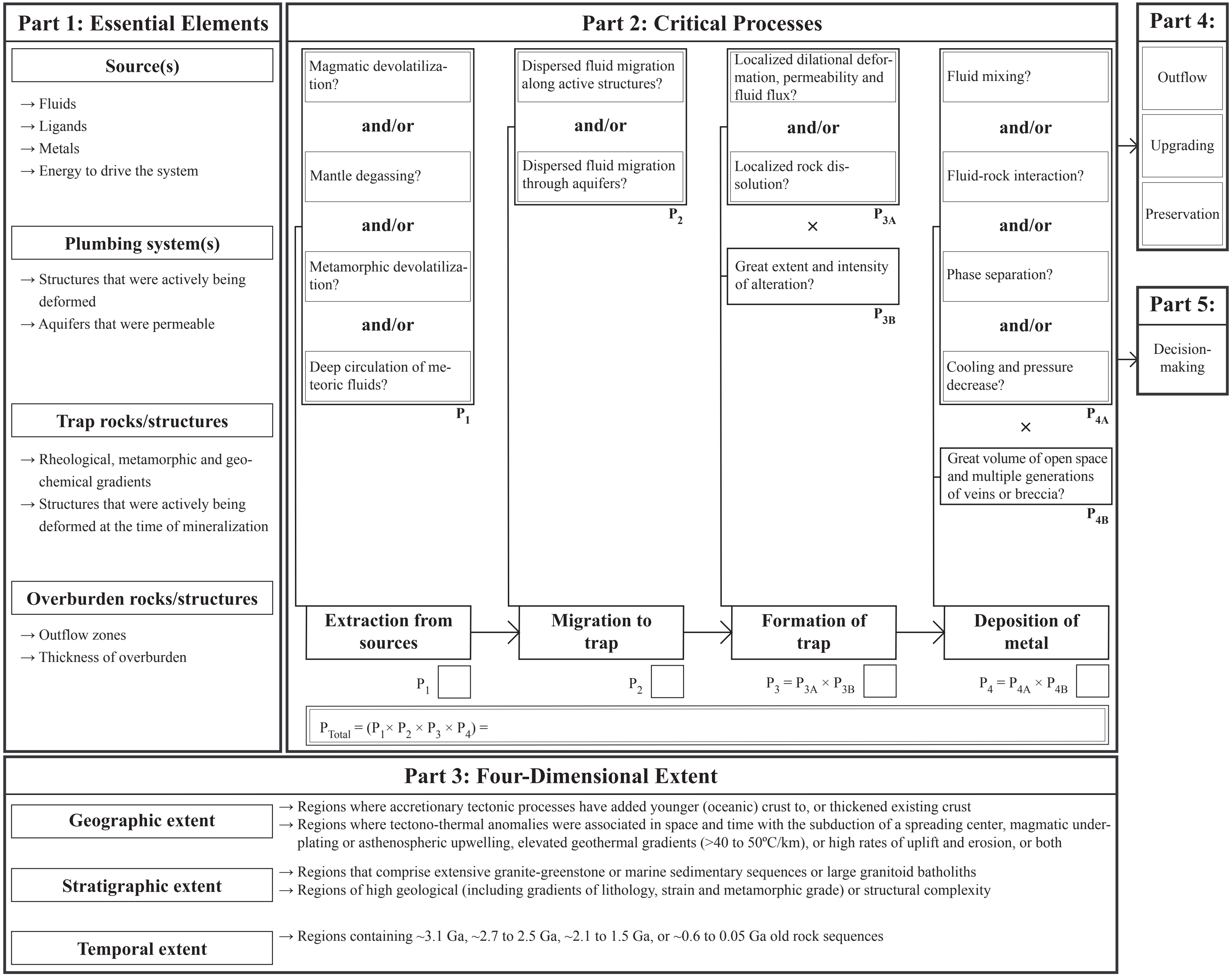
[1] For the purpose of this study all transactions were grossed up to full project value and converted to Australian dollars of 2004

Key to abbreviations: NPV = net present value; IRR = internal rate of return

Table 3. Definition of exploration stages (modified from Lord et al., 2001)

| Stage | Objective | Milestones |
|---|---|---|
| A | Project generation | Select and acquire ground in well endowed belts<br>Establish data base and management system<br>Build an expert team for the belt |
| B | Prospect definition (reconnaissance) | Build area knowledge<br>Test presence of mineralizing system<br>Define prospect risks<br>Define drillable targets |
| C | Systematic drill testing of targets | Establish size and grade potential<br>Test potential of mineralizing system<br>Test geologic information<br>Test geologic and mineralization models |
| D | Resource delineation | Test continuity<br>Establish controls on grade distribution |
| E | Feasibility | Establish economic / metallurgical parameters<br>Determine net present value (NPV)<br>Determine project costs |

Appendix 2 - Figure 1.



**Part 1: Essential Elements**

**Source(s)**
- → Fluids
- → Ligands
- → Metals
- → Energy to drive the system

**Plumbing system(s)**
- → Structures that were actively being deformed
- → Aquifers that were permeable

**Trap rocks/structures**
- → Rheological, metamorphic and geochemical gradients
- → Structures that were actively being deformed at the time of mineralization

**Overburden rocks/structures**
- → Outflow zones
- → Thickness of overburden

**Part 2: Critical Processes**

Magmatic devolatilization?
**and/or**
Mantle degassing?
**and/or**
Metamorphic devolatilization?
**and/or**
Deep circulation of meteoric fluids?
$P_1$

Dispersed fluid migration along active structures?
**and/or**
Dispersed fluid migration through aquifers?
$P_2$

Localized dilational deformation, permeability and fluid flux?
**and/or**
Localized rock dissolution?
$P_{3A}$
×
Great extent and intensity of alteration?
$P_{3B}$

Fluid mixing?
**and/or**
Fluid-rock interaction?
**and/or**
Phase separation?
**and/or**
Cooling and pressure decrease?
$P_{4A}$
×
Great volume of open space and multiple generations of veins or breccia?
$P_{4B}$

**Extraction from sources** → **Migration to trap** → **Formation of trap** → **Deposition of metal**

$P_1$ ☐
$P_2$ ☐
$P_3 = P_{3A} \times P_{3B}$ ☐
$P_4 = P_{4A} \times P_{4B}$ ☐

$P_{Total} = (P_1 \times P_2 \times P_3 \times P_4) =$

**Part 4:**
- Outflow
- Upgrading
- Preservation

**Part 5:**
Decision-making

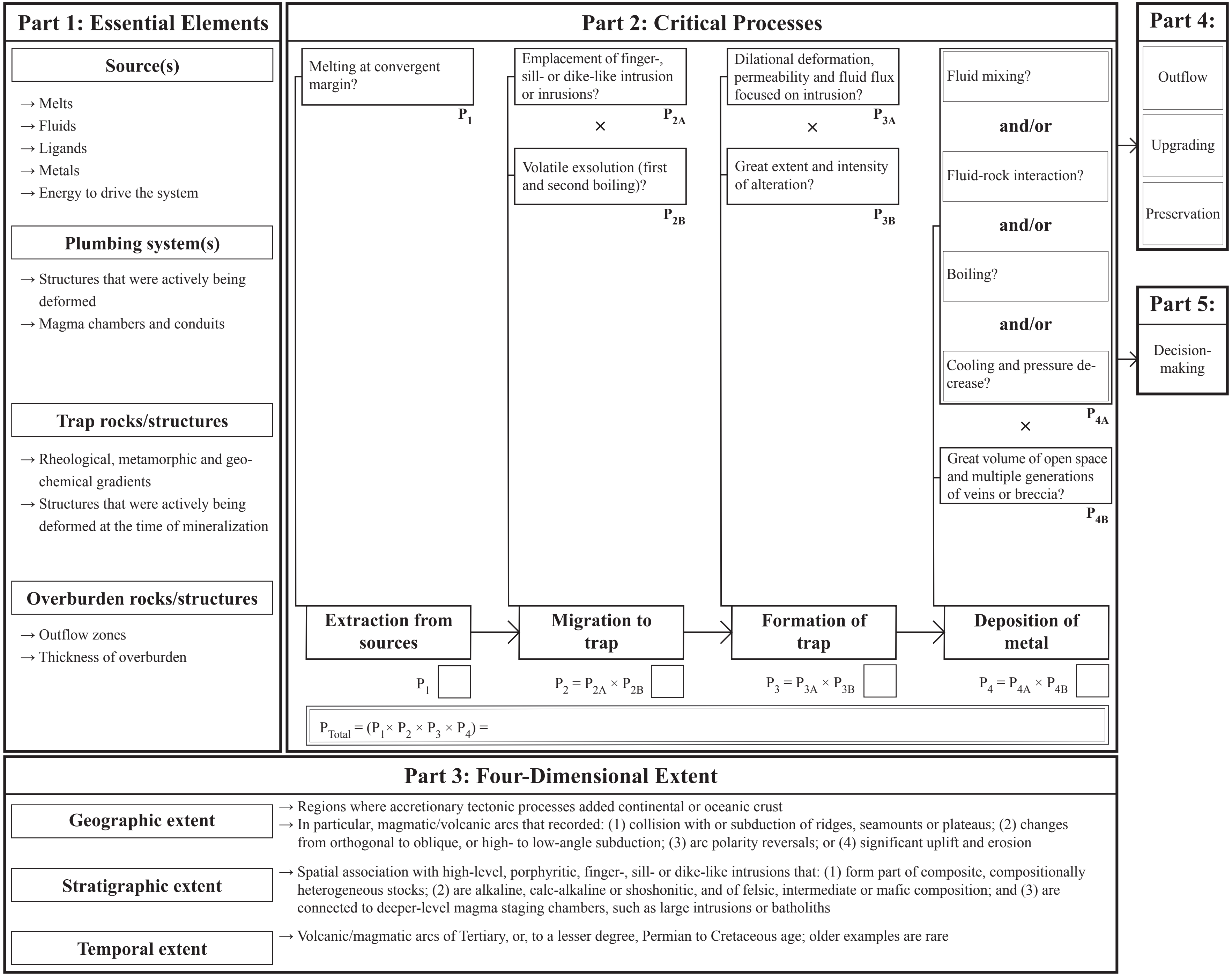
**Part 3: Four-Dimensional Extent**

**Geographic extent**
- → Regions where accretionary tectonic processes have added younger (oceanic) crust to, or thickened existing crust
- → Regions where tectono-thermal anomalies were associated in space and time with the subduction of a spreading center, magmatic underplating or asthenospheric upwelling, elevated geothermal gradients (>40 to 50ºC/km), or high rates of uplift and erosion, or both

**Stratigraphic extent**
- → Regions that comprise extensive granite-greenstone or marine sedimentary sequences or large granitoid batholiths
- → Regions of high geological (including gradients of lithology, strain and metamorphic grade) or structural complexity

**Temporal extent**
- → Regions containing ~3.1 Ga, ~2.7 to 2.5 Ga, ~2.1 to 1.5 Ga, or ~0.6 to 0.05 Ga old rock sequences

Appendix 2 - Figure 2.



**Part 1: Essential Elements**

**Source(s)**

- → Melts
- → Fluids
- → Ligands
- → Metals
- → Energy to drive the system

**Plumbing system(s)**

- → Structures that were actively being deformed
- → Magma chambers and conduits

**Trap rocks/structures**

- → Rheological, metamorphic and geochemical gradients
- → Structures that were actively being deformed at the time of mineralization

**Overburden rocks/structures**

- → Outflow zones
- → Thickness of overburden

**Part 2: Critical Processes**

Melting at convergent margin? $P_1$

**Extraction from sources** → $P_1$ ☐

Emplacement of finger-, sill- or dike-like intrusion or inrusions? $P_{2A}$

×

Volatile exsolution (first and second boiling)? $P_{2B}$

**Migration to trap** → $P_2 = P_{2A} \times P_{2B}$ ☐

Dilational deformation, permeability and fluid flux focused on intrusion? $P_{3A}$

×

Great extent and intensity of alteration? $P_{3B}$

**Formation of trap** → $P_3 = P_{3A} \times P_{3B}$ ☐

Fluid mixing?

**and/or**

Fluid-rock interaction?

**and/or**

Boiling?

**and/or**

Cooling and pressure decrease?

$P_{4A}$

×

Great volume of open space and multiple generations of veins or breccia? $P_{4B}$

**Deposition of metal** $P_4 = P_{4A} \times P_{4B}$ ☐

$P_{Total} = (P_1 \times P_2 \times P_3 \times P_4) =$

**Part 4:**

Outflow

Upgrading

Preservation

**Part 5:**

Decision-making

**Part 3: Four-Dimensional Extent**

**Geographic extent**

- → Regions where accretionary tectonic processes added continental or oceanic crust
- → In particular, magmatic/volcanic arcs that recorded: (1) collision with or subduction of ridges, seamounts or plateaus; (2) changes from orthogonal to oblique, or high- to low-angle subduction; (3) arc polarity reversals; or (4) significant uplift and erosion

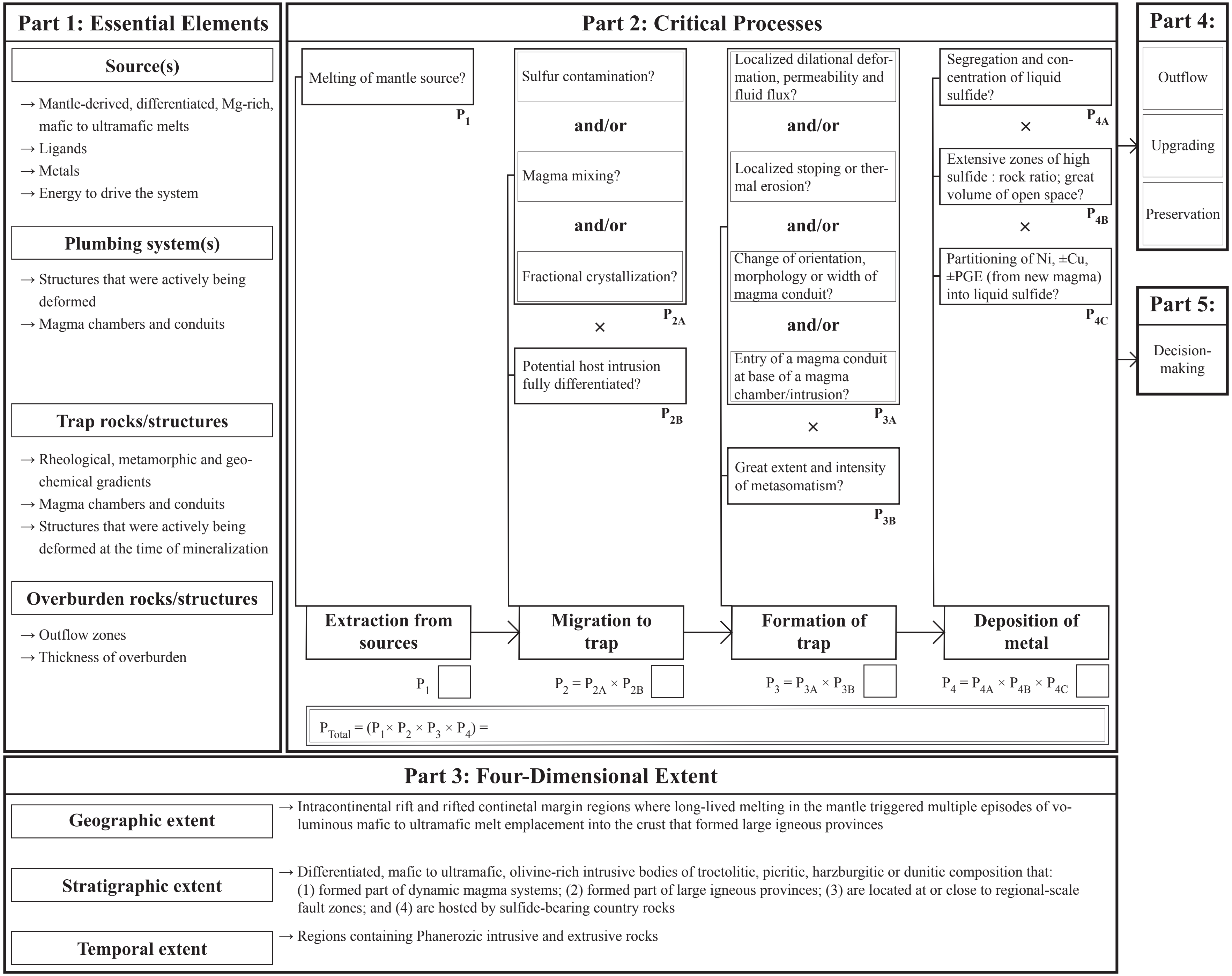
**Stratigraphic extent**

- → Spatial association with high-level, porphyritic, finger-, sill- or dike-like intrusions that: (1) form part of composite, compositionally heterogeneous stocks; (2) are alkaline, calc-alkaline or shoshonitic, and of felsic, intermediate or mafic composition; and (3) are connected to deeper-level magma staging chambers, such as large intrusions or batholiths

**Temporal extent**

- → Volcanic/magmatic arcs of Tertiary, or, to a lesser degree, Permian to Cretaceous age; older examples are rare

# Appendix 2 - Figure 3.



**Part 1: Essential Elements**

**Source(s)**

→ Mantle-derived, differentiated, Mg-rich, mafic to ultramafic melts
→ Ligands
→ Metals
→ Energy to drive the system

**Plumbing system(s)**

→ Structures that were actively being deformed
→ Magma chambers and conduits

**Trap rocks/structures**

→ Rheological, metamorphic and geochemical gradients
→ Magma chambers and conduits
→ Structures that were actively being deformed at the time of mineralization

**Overburden rocks/structures**

→ Outflow zones
→ Thickness of overburden

**Part 2: Critical Processes**

**Extraction from sources**

Melting of mantle source? $P_1$

$P_1$ ☐

**Migration to trap**

Sulfur contamination? and/or Magma mixing? and/or Fractional crystallization? $P_{2A}$

×

Potential host intrusion fully differentiated? $P_{2B}$

$P_2 = P_{2A} \times P_{2B}$ ☐

**Formation of trap**

Localized dilational deformation, permeability and fluid flux? and/or Localized stoping or thermal erosion? and/or Change of orientation, morphology or width of magma conduit? and/or Entry of a magma conduit at base of a magma chamber/intrusion? $P_{3A}$

×

Great extent and intensity of metasomatism? $P_{3B}$

$P_3 = P_{3A} \times P_{3B}$ ☐

**Deposition of metal**

Segregation and concentration of liquid sulfide? $P_{4A}$

×

Extensive zones of high sulfide : rock ratio; great volume of open space? $P_{4B}$

×

Partitioning of Ni, ±Cu, ±PGE (from new magma) into liquid sulfide? $P_{4C}$

$P_4 = P_{4A} \times P_{4B} \times P_{4C}$ ☐

$P_{Total} = (P_1 \times P_2 \times P_3 \times P_4) =$

**Part 4:**

Outflow
Upgrading
Preservation

**Part 5:**

Decision-making

**Part 3: Four-Dimensional Extent**

**Geographic extent**

→ Intracontinental rift and rifted continetal margin regions where long-lived melting in the mantle triggered multiple episodes of voluminous mafic to ultramafic melt emplacement into the crust that formed large igneous provinces

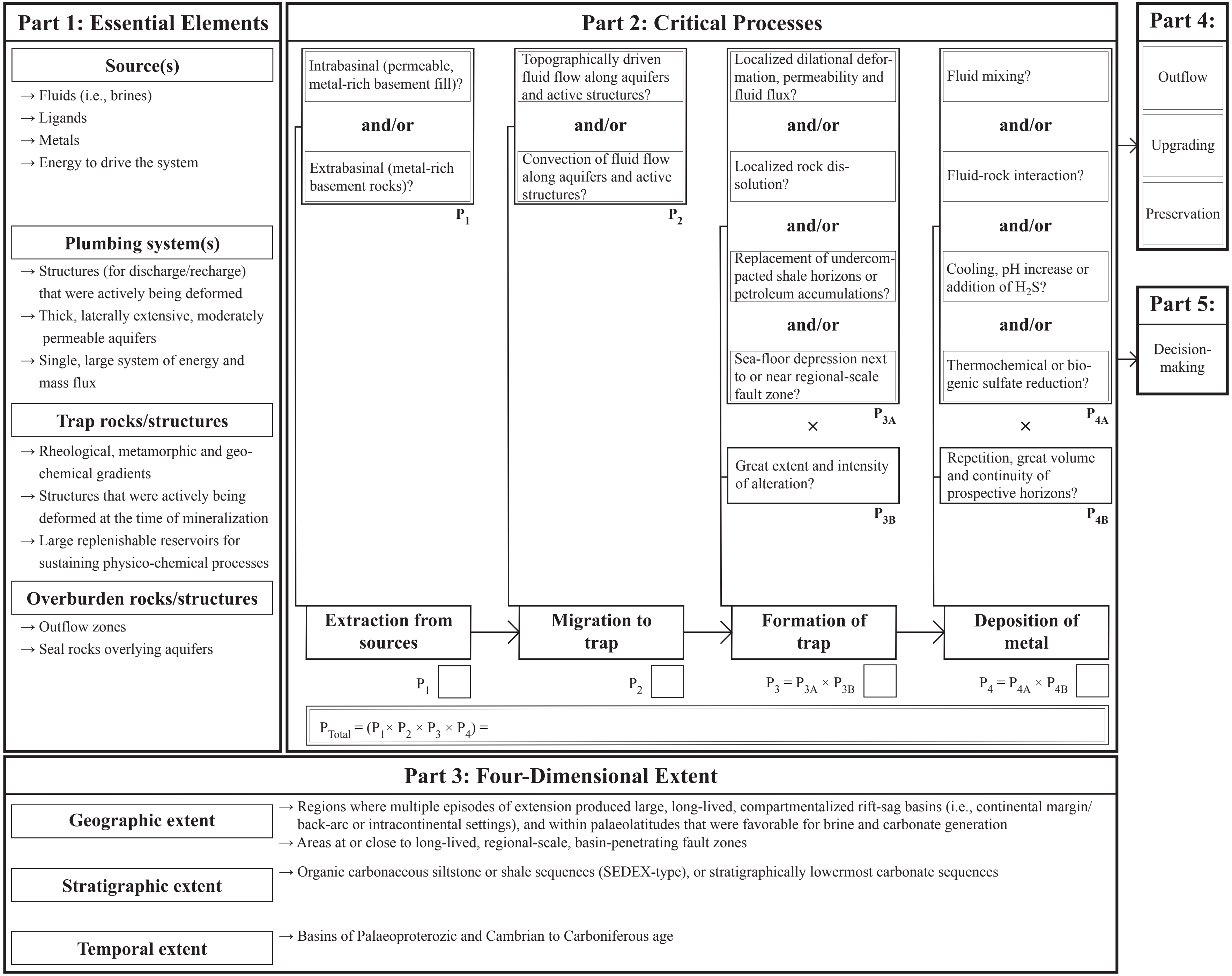
**Stratigraphic extent**

→ Differentiated, mafic to ultramafic, olivine-rich intrusive bodies of troctolitic, picritic, harzburgitic or dunitic composition that: (1) formed part of dynamic magma systems; (2) formed part of large igneous provinces; (3) are located at or close to regional-scale fault zones; and (4) are hosted by sulfide-bearing country rocks

**Temporal extent**

→ Regions containing Phanerozic intrusive and extrusive rocks

Appendix 2 - Figure 4.



**Part 1: Essential Elements**

**Source(s)**
- → Fluids (i.e., brines)
- → Ligands
- → Metals
- → Energy to drive the system

**Plumbing system(s)**
- → Structures (for discharge/recharge) that were actively being deformed
- → Thick, laterally extensive, moderately permeable aquifers
- → Single, large system of energy and mass flux

**Trap rocks/structures**
- → Rheological, metamorphic and geochemical gradients
- → Structures that were actively being deformed at the time of mineralization
- → Large replenishable reservoirs for sustaining physico-chemical processes

**Overburden rocks/structures**
- → Outflow zones
- → Seal rocks overlying aquifers

**Part 2: Critical Processes**

Intrabasinal (permeable, metal-rich basement fill)?
**and/or**
Extrabasinal (metal-rich basement rocks)?
$P_1$

Topographically driven fluid flow along aquifers and active structures?
**and/or**
Convection of fluid flow along aquifers and active structures?
$P_2$

Localized dilational deformation, permeability and fluid flux?
**and/or**
Localized rock dissolution?
**and/or**
Replacement of undercompacted shale horizons or petroleum accumulations?
**and/or**
Sea-floor depression next to or near regional-scale fault zone?
$P_{3A}$
×
Great extent and intensity of alteration?
$P_{3B}$

Fluid mixing?
**and/or**
Fluid-rock interaction?
**and/or**
Cooling, pH increase or addition of $H_2S$?
**and/or**
Thermochemical or biogenic sulfate reduction?
$P_{4A}$
×
Repetition, great volume and continuity of prospective horizons?
$P_{4B}$

**Extraction from sources** → **Migration to trap** → **Formation of trap** → **Deposition of metal**

$P_1$ ☐
$P_2$ ☐
$P_3 = P_{3A} \times P_{3B}$ ☐
$P_4 = P_{4A} \times P_{4B}$ ☐

$P_{Total} = (P_1 \times P_2 \times P_3 \times P_4) =$

**Part 4:**
- Outflow
- Upgrading
- Preservation

**Part 5:**
Decision-making

**Part 3: Four-Dimensional Extent**

**Geographic extent**
- → Regions where multiple episodes of extension produced large, long-lived, compartmentalized rift-sag basins (i.e., continental margin/back-arc or intracontinental settings), and within palaeolatitudes that were favorable for brine and carbonate generation
- → Areas at or close to long-lived, regional-scale, basin-penetrating fault zones

**Stratigraphic extent**
- → Organic carbonaceous siltstone or shale sequences (SEDEX-type), or stratigraphically lowermost carbonate sequences

**Temporal extent**
- → Basins of Palaeoproterozic and Cambrian to Carboniferous age