Mineral Resource Assessment Methodologies

Deposit Models and Their Application in Mineral Resource Assessments

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Abstract

Mineral deposit models are important in quantitative resource assessments for two reasons: (1) grades and tonnages of most deposit types are significantly different and (2) types occur in different geologic settings that can be identified from geologic maps. Mineral deposit models are the keystone in combining the diverse geoscience information on geology, mineral occurrences, geophysics, and geochemistry used in resource assessments and mineral exploration. Far too few thoroughly explored mineral deposits are available in most local areas for reliable identification of the important geoscience variables or for robust estimation of undiscovered deposits—thus we need mineral deposit models. Well-designed and well-constructed deposit models allow geologists to know from observed geologic environments the possible mineral deposit types that may exist and allow economists to determine the possible economic viability of these resources in the region. Thus, mineral deposit models play the central role in transforming geoscience information to a form useful to policymakers.

Descriptive and grade and tonnage models are discussed because they are the foundations upon which other kinds of models are built. Examples of deposit density models (which represent the number of deposits per unit area) and economic models are provided. Additionally, new forms of quantitative descriptive models are presented with preliminary examples of deposit mineralogy and deposits spatially associated with gold-rich and molybdenum-rich porphyry copper deposits.

Introduction

Because every mineral deposit is different from every other in some way, models have to represent more than single deposits. Deposits sharing a relatively wide variety and large number of attributes come to be characterized as a “type,” and a model representing that type can be synthesized. Probably the most important part of synthesizing mineral deposit models is the planning stage, in which consideration of the purpose and possible uses of the models should determine the character of the models. Ideally, deposit models would provide the necessary and sufficient information to discriminate (1) possible mineralized environments from barren environments, (2) types of known deposits from each other, and (3) mineral deposits from mineral occurrences. In quantitative assessments, deposit models are used to classify mineralized and barren environments and to classify types of known deposits in the tract-delineation part of the assessment, whereas mineral deposits are distinguished from mineral occurrences in the number-of-deposits estimation part of the assessment. The grade and tonnage parts of deposit models, combined with estimation of the number of undiscovered deposits, provide the foundation for economic analysis.

Although there are many fine compendiums of mineral deposit models (Roberts and Sheahan, 1988; Sheahan and Cherry, 1993; Ekstrand and others, 1995; Rongfu, 1995; AGSO Journal of Australian Geology & Geophysics, 1998), the focus here is on deposit models applied to quantitative resource assessment. Thus, this discussion is limited to mineral deposit models specifically designed for quantitative assessments, such as those in Cox and Singer (1986), Bliss (1992a), and Rogers and others (1995). The target population of these assessments is the group of undiscovered mineral deposits in which each is defined as a mineral occurrence of such size and grade that it might, under favorable circumstances, be economic. Although history suggests that we can expect discoveries of as-yet-unrecognized deposit types, the kinds of assessments discussed here do not include resources from these deposits.

In most published quantitative mineral resource assessments, two kinds of models have been relied upon—(1) descrip-

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tive and (2) grade and tonnage. Descriptive and grade and tonnage models are discussed first because they are the foundations upon which other kinds of models are built. Examples of deposit density models (which represent the number of deposits per unit area) and economic models have appeared sparingly; each of these kinds of models is discussed briefly below. Additionally, new forms of quantitative descriptive models are discussed.

Descriptive Models

One of the purposes of a mineral deposit model is to communicate information that helps people to find and evaluate mineral deposits. A mineral deposit model is the systematically arranged information describing the essential attributes (properties) of a class of mineral deposits (Barton, 1993).

Descriptive models, such as those in Cox and Singer (1986), have two parts (table 1). The first describes the geologic environments in which the deposits are found; the second gives identifying characteristics of deposits. The first, the "Geological Environment," provides information under several headings. The headings "Rock Types" and "Textures" describe the favorable host rocks of deposits, as well as the source rocks believed responsible for some deposits. "Age Range" refers to the age of the event responsible for the formation of the deposit. "Depositional Environment" refers to the geologic setting of the deposit. "Tectonic Setting" is concerned with major tectonic features or provinces. "Associated Deposit Types" are listed as deposit types whose presence might indicate suitable conditions for the

Table 1. Example of the descriptive model for porphyry Cu-Mo deposits from Cox (1986).

DESCRIPTIVE MODEL OF PORPHYRY Cu-Mo

MODEL 21a

By Dennis P. Cox

DESCRIPTION Stockwork veinlets of quartz, chalcopyrite, and molybdenite in or near a porphyritic intrusion. Ratio of Au (in ppm [parts per million]) to Mo (in percent) less than 3.

GENERAL REFERENCE Titley (1982).

GEOLOGICAL ENVIRONMENT

Rock Types Tonalite to monzogranite stocks and breccia pipes intrusive into batholithic, volcanic, or sedimentary rocks.

Textures Intrusions contemporaneous with ore commonly are porphyries with fine- to medium-grained aplitic groundmass. Porphyry texture may be restricted to small dikes in some deposits (Brenda).

Age Range Mainly Mesozoic to Tertiary, but can be any age.

Depositional Environment High-level intrusive porphyry contemporaneous with abundant dikes, faults, and breccia pipes. Cupolas of batholiths.

Tectonic Setting(s) Numerous faults in subduction-related volcanic plutonic arcs. Mainly along continental margins but also in oceanic convergent plate boundaries.

Associated Deposit Types Cu, Zn, or Fe skarns may be rich in gold, gold + base-metal sulfosalts in veins, gold placers. Volcanic-hosted massive replacement and polymetallic replacement.

DEPOSIT DESCRIPTION

Mineralogy Chalcopyrite + pyrite + molybdenite. Peripheral vein or replacement deposits with chalcopyrite + sphalerite + galena ± gold. Outermost zone may have veins of Cu-Ag-Sb-sulfides, barite, and gold.

Texture/Structure Veinlets and disseminations or massive replacement of favorable country rocks.

Alteration Quartz + K-feldspar + biotite (chlorite) ± anhydrite (potassic alteration) grading outward to propylitic. Late white mica + clay (phyllic) alteration may form capping or outer zone or may affect the entire deposit. High-alumina alteration assemblages may be present in upper levels of the system.

Ore Controls Ore grade is, in general, positively correlated with spacing of veinlets and mineralized fractures. Country rocks favorable for mineralization are calcareous sediments; diabase, tonalite, or diorite.

Weathering Intense leaching of surface; wide areas of iron oxide stain. Fractures coated with hematitic limonite. Supergene copper as chalcocite may form blanket below leached zone. Residual soils may contain anomalous amounts of rutile.

Geochemical Signature Cu + Mo + Ag ± W + B + Sr center; Pb, Zn, Au, As, Sb, Se, Te, Mn, Co, Ba, and Rb in outer zone. Locally Bi and Sn form distal anomalies. High S in all zones. Ratio of Au (ppm): Mo (percent) less than 3. Magnetic low.

EXAMPLES

Brenda, CNBC	(Soregaroli and Whitford, 1976)
Sierrita Esperanza, USAZ	(West and Aiken, 1982)

formation of deposits of the type portrayed by the model. Thus, this part of the model uses information from the geologic map, geophysical maps, and the known deposits and occurrences. The second part of the descriptive model, the "Deposit Description," provides the identifying characteristics of the deposits themselves, particularly emphasizing aspects by which the deposits might be recognized, such as mineralogy, alteration, and geochemical and geophysical anomalies.

The first part of a descriptive model describes the general setting of the deposit type and plays a primary role in the delineation of tracts of land geologically permissive for the occurrence of undiscovered deposits. The second part helps classify known deposits and occurrences into types, which aids the delineation process. In some cases, the types of known deposits and occurrences identify geologic environments not indicated on geologic maps. The organization of the models constitutes a classification of deposits. The arrangement used emphasizes easy access to the models by focusing on host-rock lithology and tectonic setting, the features most easily obtained from a geologic map.

Grade and Tonnage Models

Frequency distributions of tonnages and average grades of well-explored deposits of each type are used as models for grades and tonnages of undiscovered deposits of the same type in geologically similar settings. Grade and tonnage models (Cox and Singer, 1986; Bliss, 1992a) combined with estimates of number of undiscovered deposits are the fundamental means of translating geologists' resource assessments into a language that economists can use. Grade and tonnage models specifically prepared for assessments, such those cited above, show the frequencies of different sizes (for example, fig. 1) and grades (for example, fig. 2) of each of more than 60 mineral deposit types based on more than 2,500 deposits from around the world. For each deposit type, these models help define a deposit, as opposed to a mineral occurrence or a weak manifestation of an ore-forming process. Data utilized to construct these models include average grades of each metal or mineral commodity of possible economic interest and the associated tonnage based on the total production, reserves, and resources at the lowest possible cutoff grade. These data represent an estimate of the endowment of each of many known deposits so that the final models can accurately represent the endowment of all undiscovered deposits (Singer, 1994a).

An important consideration at the data-gathering stage is the question of what the sampling unit should be (Cox and others, 1986; Singer, 1993). Grade and tonnage data are available to varying degrees for districts, deposits, mines, and shafts. In many cases, old production data are available for some deposits, and recent resource estimates are available for other deposits. Prob-

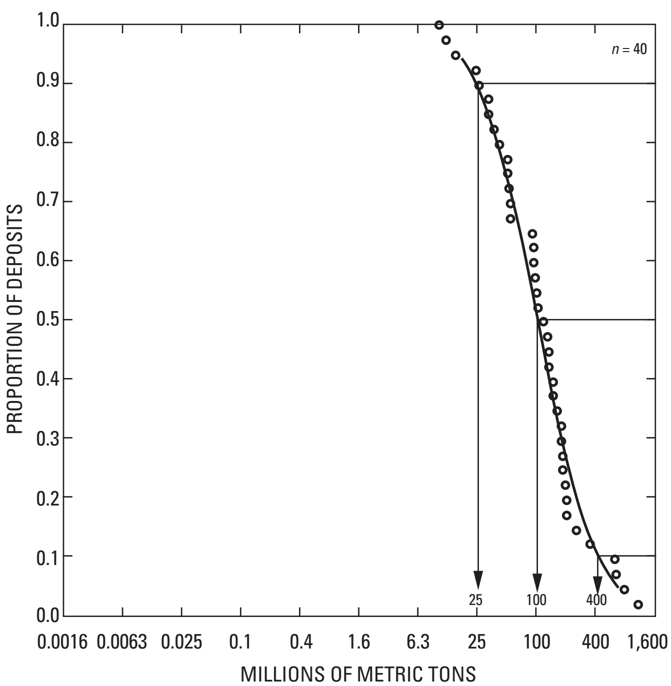

Figure 1. Example of tonnage part of model for porphyry Cu-Au deposits (modified from Singer and Cox, 1986, fig. 78). Each dot represents an individual deposit. Deposits are cumulated in ascending grade or tonnage. Smoothed curves, representing percentiles of a lognormal distribution having the same mean and standard deviation as observed data, are plotted through the points. Intercepts for the 90th, 50th, and 10th percentiles of the lognormal distributions are constructed.

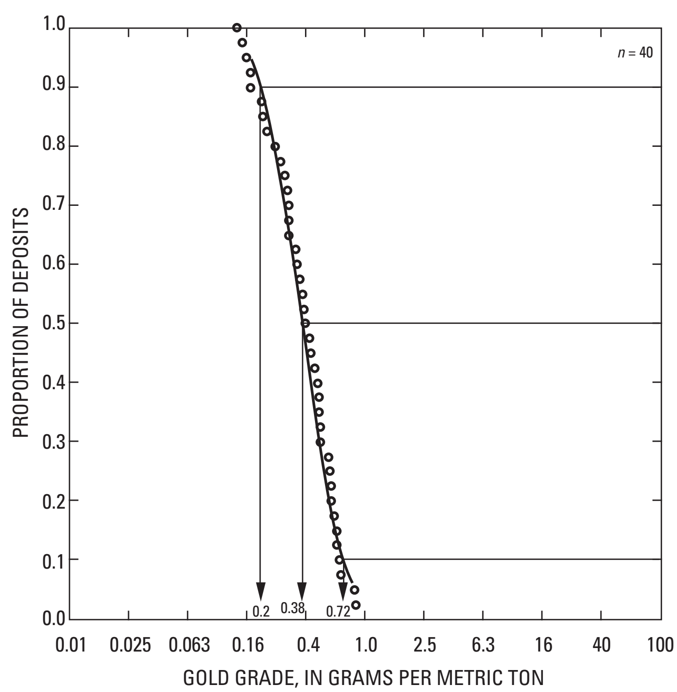

Figure 2. Example of gold grade part of model for porphyry Cu-Au deposits (modified from Singer and Cox, 1986, fig. 80). Each dot represents an individual deposit. Deposits are cumulated in ascending grade or tonnage. Smoothed curves, representing percentiles of a lognormal distribution having the same mean and standard deviation as observed data, are plotted through the points. Intercepts for the 90th, 50th, and 10th percentiles of the lognormal distributions are constructed.

ably the most common error in constructing grade and tonnage models is mixing old production data from some deposits with resource data from other deposits. It is critical that all data used in the model represent the same sampling unit because mixing data from deposits and districts, or old production and recent resource estimates, usually produces bimodal or at least nonlognormal distributions and may introduce correlations among the variables that are artifacts of the mixed sampling units. Models constructed by using data from mixed sampling units are of questionable value because the frequencies of tonnage and grade observed are directly related to the proportion of deposits from each sampling unit and are unlikely to be representative of the proportion in the undiscovered deposits being estimated in an assessment.

It has been suggested that the grade and tonnage models should be extended to include not only deposits but also occurrences, which are typically very small concentrations of a mineral. If the problem of possible biases due to incomplete exploration of these occurrences is neglected, then it is possible to construct such models; the tonnage model would of course have a much lower median. Because quantitative assessments require that the estimated number of undiscovered deposits be consistent with the grade and tonnage model, the process of estimating the number of deposits might be more difficult because of the much larger number of "deposits" (including occurrences) to be estimated. An economic analysis of the results of this assessment would show that the occurrences and probably some of the estimated undiscovered deposits would be uneconomic. Thus, the effect of including occurrences in the grade and tonnage model would be to make more work in the assessment and not affect the final answer in any way.

The application of these models to resource assessments helps to identify how the models should be augmented. To avoid the situation where every deposit is considered unique and therefore prediction is not possible, the deposits in an area should be tested to determine if they are different from the general model. If the well-explored (that is, completely drilled) deposits are significantly different in size or grade, then the local deposits should be examined to see if they belong to a geologically homogeneous subset of the original grade and tonnage model. Only if all of these conditions are met should a new submodel be constructed, along with a consistent descriptive model. The revised model would then be used in conjunction with the number of deposits estimates.

Deposit Density Models

A key function of many quantitative mineral resource assessments is estimation of the number of undiscovered deposits. Numerous techniques can be used directly or as guidelines to make these estimates. Most robust of these methods is a form of mineral deposit model wherein the numbers of deposits per unit area from well-explored regions are counted (Bliss and Menzie, 1993) and the resulting frequency distribution is used either directly for an estimate or indirectly as a guideline in some other method. Ratios of number of deposits per unit area can be used in histograms to show how common are different deposit densities. It is not necessary that the base areas be explored completely, but it is necessary that

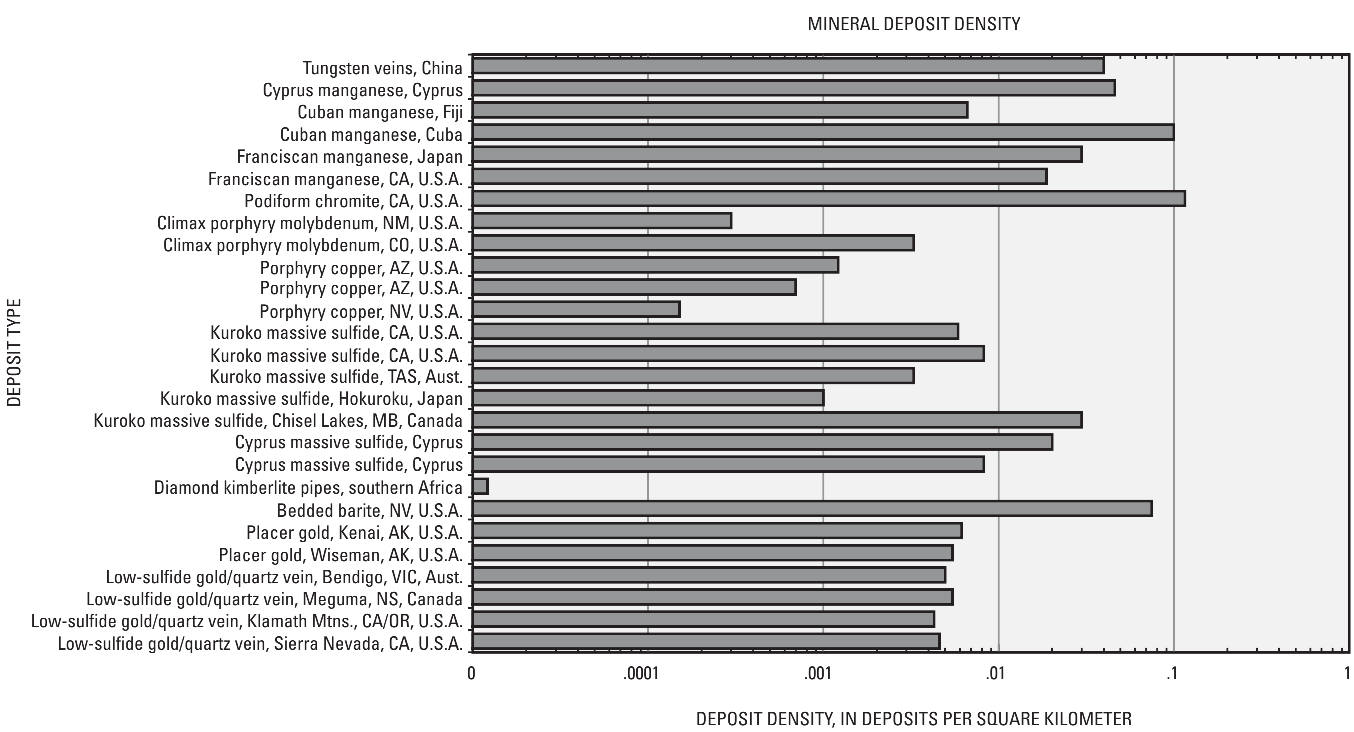

Figure 3. Graph of numbers of deposits per unit area by deposit type from well-explored regions, as reported by Singer and others (2001). MB, Manitoba; NS, Nova Scotia; TAS, Tasmania; VIC, Victoria.

the number of deposits found and the proportion of the area explored be estimated. Examples of mineral deposit density models were presented by Bliss (1992b), Bliss and Menzie (1993), and Singer (1994b). Singer and others (2001) summarized these estimates and added new deposit densities (fig. 3). As in the case of other kinds of models designed for quantitative resource assessment, deposit density models need to be constructed so that they are consistent with these other models.

For example, densities for low-sulfide quartz gold vein deposits were discussed by Bliss and Menzie (1993). These mesothermal deposits were defined in the descriptive model, and the deposit density model also was consistent with the grade and tonnage model. It is important to note that the same proximity rule used to construct the grade and tonnage model (workings within 1.6 kilometers of each other were treated as part of the same deposit) was used to define deposits for the deposit densities.

Many of the specially selected areas where deposit densities have been reported (fig. 3) provide standards to identify what should be high estimates of number of undiscovered deposits in most situations. Thus, many of these examples probably are best considered as guides to upper limits of the density of deposits. General deposit density models that can be used for estimating the number of deposits, given the area of the permissive tract, were provided for podiform chromite deposits (Singer, 1994b) and for porphyry copper deposits (Singer and others, 2005).

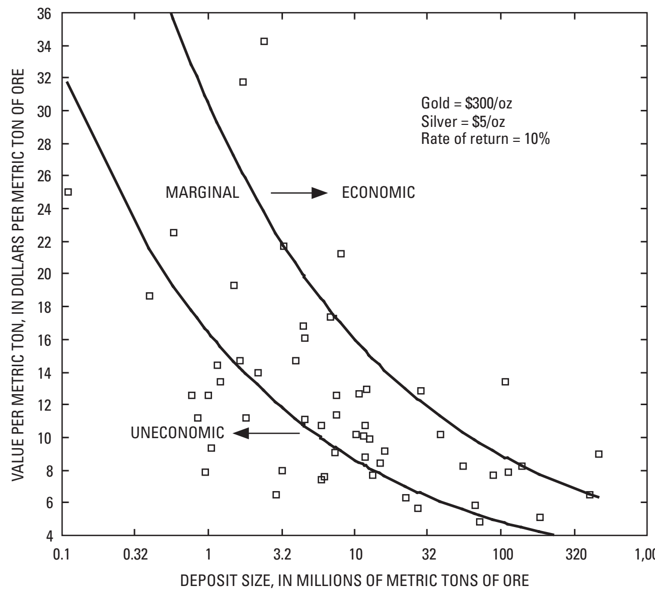

Figure 4. Graph showing relation between value per metric ton and deposit size (in millions of metric tons of ore) for some U.S. open-pit, heap-leach gold-silver deposits when prices and the rate of return are as shown.

Economic Models

In resource assessments of undiscovered mineral deposits and in the early stages of exploration, including planning, a need exists for prefeasibility cost models. These models, which separate economic from uneconomic deposits, help to focus on targets that can benefit the exploration enterprise. In resource assessment, these models can be used to eliminate deposits that would probably be uneconomic even if discovered. As noted by Singer (1993), varying numbers of deposits used to construct the grade and tonnage models are not, or were not, economic. The former U.S. Bureau of Mines (USBM) previously developed simplified cost models for such problems (Camm, 1991). These cost models estimate operating and capital expenditures for a mineral deposit, given the appropriate mining method and the deposit's tonnage, grade, and depth. These cost models also were incorporated in USBM prefeasibility software (Smith, 1992).

In a previous study (Singer and others, 1998), Camm's simplified cost models for U.S. open-pit gold-silver deposit operations were modified to reflect higher capacities observed in heap-leach processing with autoclave, carbon-in-leach, carbon-in-pulp, and Merrill Crowe mills. For heap-leach operations, equations for estimating operating cost and capital expenditure also were modified. Explanations of these various processing methods are available in Camm (1991). For a particular tonnage, the dividing (or break-even) line between economic and uneconomic can be estimated by adding the estimated operating cost to the capital expenditure divided by capacity times operating days per year times the present value of a dollar for the life of the mine. To account for variation and uncertainties in most of the inputs to these estimates, 0.7 and 1.3 of this break-even value are plotted to estimate boundaries for uneconomic, marginal, and economic deposits (fig. 4).

For underground mining of massive sulfide deposits using each of five different mining methods, capacity and cost estimates using the USBM models with observed mines were compared (Singer and others, 2000). Based on analysis of the economic relations in mines on 28 massive sulfide deposits in this study, no reason was found to reject the simplified cost models for underground mining operations presented by Camm (1991). The deposits represent at least six different deposit types and are located in seven different countries. For cut-and-fill, room-and-pillar, crater retreat, shrinkage stope, and sublevel longhole mining, with or without shafts, the equations for estimating operating cost and capital expenditure are consistent with known operations. The resultant equations appear to provide reasonable estimates of costs (fig. 5). Similar results were found for open-pit mining and heap-leach recovery of copper deposits in the United States (Long and Singer, 2001). Camm's methods and subsequent refinements have been incorporated in a computer program used to combine estimated number of deposits with grade and tonnage models (Duval, 2004). Nonetheless, all such estimates can be wrong because of factors such as poor metal recovery or errors in estimated future metal prices.

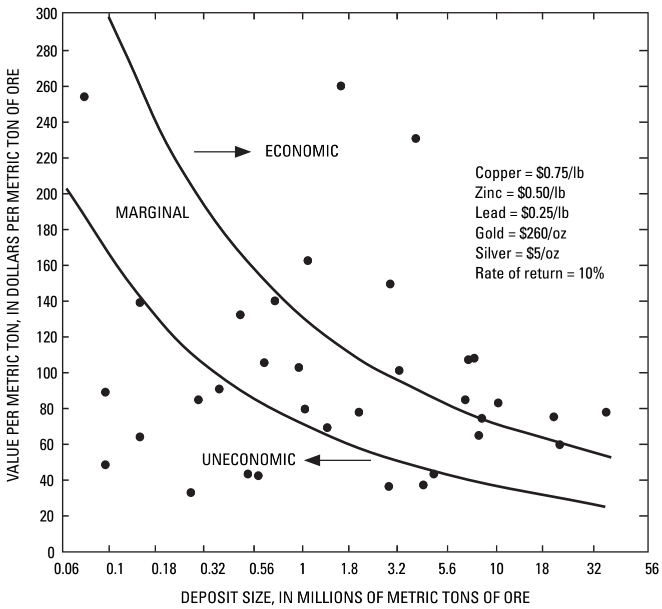

Figure 5. Graph showing relation between value per metric ton and deposit size (in millions of metric tons of ore) for some zinc-lead skarn deposits. All deposits are assumed to be mined at a depth of 800 feet, with half of each mined by cut-and-fill methods and half by shrinkage stope methods. Prices and the rate of return are shown in the graph.

Quantitative Models

The descriptive models discussed above have been developed on the basis of expert knowledge. An alternative, more time consuming, method of developing descriptive models is to gather data from well-explored deposits of each type to determine how commonly different attributes and combinations of attributes occur. Quantifying mineral deposit attributes is the necessary and sufficient next step in statistically classifying known deposits by type. To determine if quantified mineral deposit models would be useful, data on the minerals reported present in 55 different types of deposits were compiled (Singer and others, 1997) and were used to statistically discriminate 8 of the deposit types. Using 58 minerals and 6 generalized rock types, over 90 percent of the unknown deposits were accurately classified into the correct eight types (Singer and Kouda, 1997); clearly digital mineralogy can be useful in classifying well-studied deposits. An example of the usefulness of this kind of data is shown by a plot (fig. 6) of a few of the minerals present in three subtypes of porphyry copper deposits. Gold, alunite, covellite, and actinolite are more common in gold-rich porphyry copper deposits, whereas pyrrhotite, fluorite, and rutile are more common in the more deeply emplaced molybdenum-rich porphyry copper deposits. Although based on preliminary data, a similar pattern emerges when one looks at the proportion of porphyry copper deposits that have other deposit types within 10 kilometers of the porphyry (fig. 7). Epithermal quartz-alunite gold-silver, epithermal Comstock gold-silver, and polymetallic replacement zinc-lead are more common near gold-rich porphyry copper deposits, but zinc-lead skarn deposits are more common near molybdenum-rich porphyry copper deposits.

This kind of information is necessary but not sufficient to discriminate barren from mineralized environments; quantifying the attributes of barren environments also is necessary for this task. To be useful in quantitative assessments, the

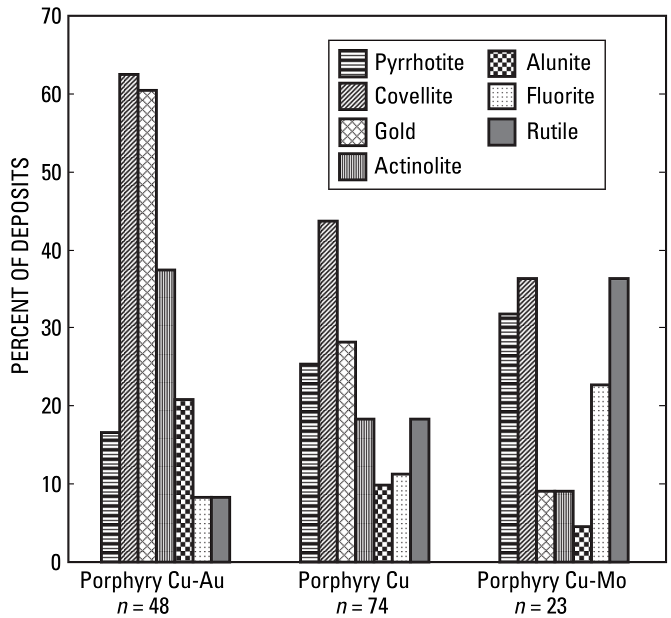

Figure 6. Graph showing the proportion of subtypes of porphyry copper deposits reporting the presence of several mineral species.

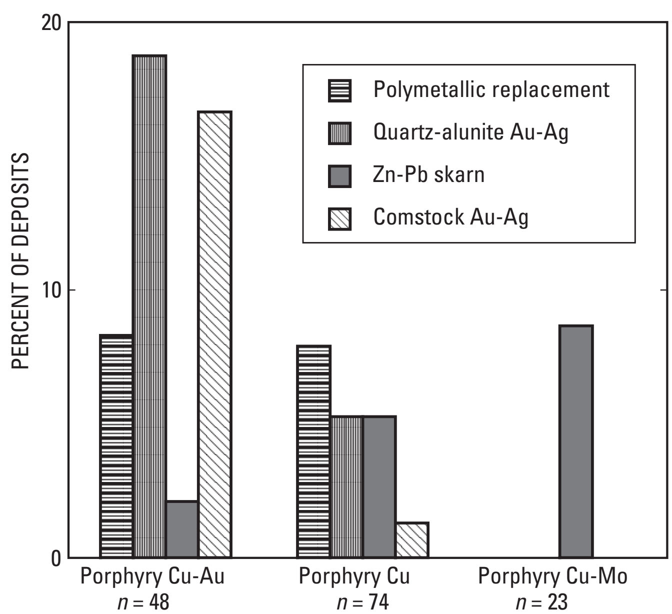

Figure 7. Graph showing the proportion of subtypes of porphyry copper deposits reporting the presence of different deposit types occurring within 10 kilometers.

models of number of deposits per unit area and the attempts to quantify deposit attributes must be constructed so that they are consistent with the present descriptive and grade and tonnage models. Otherwise, the resulting resource assessments will be internally inconsistent.

Conclusions

Consistency in quantitative assessments is dependent on the internal consistency required in the construction of the descriptive, grade and tonnage, and deposit density models. New models of number of deposits per unit area and other quantitative extensions to the present models also need to be consistent with the other parts of the models. That is, these models must be constructed from deposits that are located in geologic settings that match the descriptive models and that are consistent with the appropriate grade and tonnage models. These new versions of deposit models, the quantification of models in general, and the development of guidelines or direct methods of estimation of number of undiscovered deposits will all be successful to the extent that they are consistent with the other models used in assessments.

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