Estimating Amounts of Undiscovered Mineral Resources

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Abstract

The purpose of the three-part form of mineral resource assessments is to make unbiased quantitative assessments in a format needed in decision-support systems so that consequences of alternative courses of action can be examined. It is argued that the internally consistent descriptive, grade and tonnage, deposit density, and economic models and the design of the three-part form of assessments reduce the chances of biased estimates of the undiscovered resources. One part of three-part assessments, mineral deposit models, is discussed in Singer and Berger (this volume). Here the principal ideas of delineation of tracts of land and estimation of the number of undiscovered mineral deposits therein are presented. Linkage of the models with delineation and with estimation of deposits further reduces possible biases. Additionally, seven guidelines and some examples are provided to reduce biases in estimates of numbers of deposits. Experience from meteorology suggests that consensus schemes perform better than individual estimators and that the best estimates are made when objective estimates such as those from guidelines are part of the information supplied to subjective estimators.

Introduction

Information from mineral resource assessments is used for making decisions concerning mineral supply, land use, the environment, development, and exploration and for shaping minerals-related domestic and foreign policy. Quantitative assessments are required to make resource assessments and their associated uncertainties explicit and reproducible and to allow economic analysis. The goal is to make unbiased quantitative assessments in a format needed in decision-support systems so that the consequences of alternative courses of action can be examined.

Of the many kinds of quantitative mineral resource assessments (Harris, 1984; Shulman and others, 1992), there is one, called a three-part assessment (Singer, 1993; Drew and others, 1999), that was designed to respond to the broad goal above. In three-part assessments, (1) areas are delineated according to the types of deposits permitted by the geology, (2) the amount of metal and some ore characteristics are estimated by means of grade and tonnage models, and (3) the number of undiscovered deposits of each type is estimated. To these parts, economic analysis and the proper combinations of the parts by simulation (Root and others, 1992) can be applied.

Considerable care must be exercised in quantitative resource assessments to prevent the introduction of biased estimates of undiscovered resources. In three-part assessments, estimates are internally consistent in that delineated tracts are consistent with descriptive models, grade and tonnage models are consistent with descriptive models, grade and tonnage models are consistent with known deposits in the area, and estimates of the number of deposits are consistent with grade and tonnage models. Biases can be introduced into these estimates either by a flawed grade and tonnage model or by the lack of consistency of the grade and tonnage model with estimates of the number of deposits.

Issues about the consistency of mineral deposit models are discussed in a companion paper (Singer and Berger, this volume), as are grade and tonnage models that are the second part of three-part assessments. In this paper, the focus is on (1) delineating tracts of land in which the geology permits the occurrence of the undiscovered deposits and (2) reducing bias in estimating the number of undiscovered deposits.

Delineation of Permissive Tracts

To be able to consistently assess the undiscovered mineral resources of regions, we delineate areas where geology permits the existence of deposits of one or more specified types. These areas, called permissive tracts, are based on geologic criteria derived from deposit models that are themselves based on studies of known deposits within and outside the study area. Permissive boundaries are defined such that the probability of deposits of the type delineated occurring outside the boundary is negligible; that is, less than 1 in 100,000.

One delineation strategy is to move boundaries outward from known deposits (fig. 1). This strategy might be considered the delineation of favorable areas; however, in three-part assessments, we try to delineate permissive areas. Although favorable areas are a subset of permissive areas, they represent very different concepts. Their boundaries will coincide only if exploration coverage is very thorough and completely effective—a fairly unusual situation. In addition, delineations of favorable areas frequently are applied in different ways by dif-

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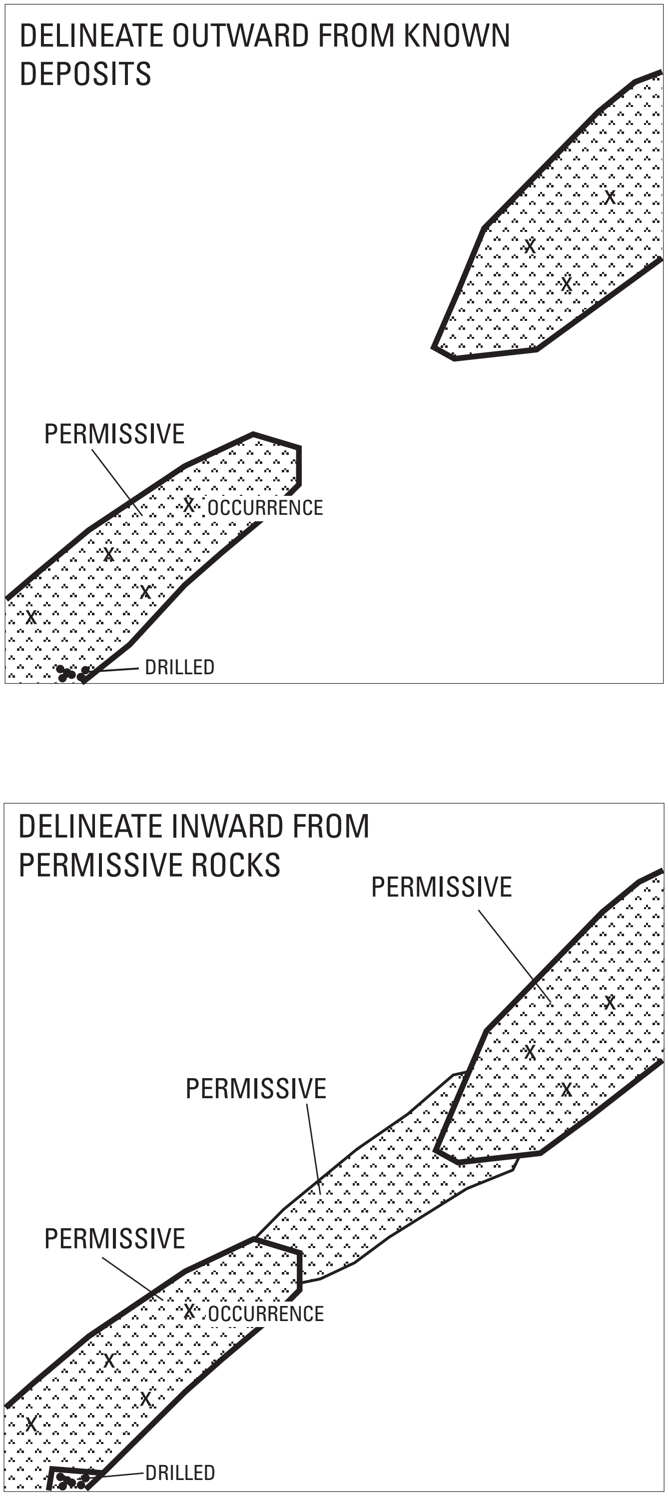

Figure 1. Maps showing delineation of tracts by two different strategies. The upper map shows the strategy of moving outward from known deposits; this strategy might be considered the delineation of favorable areas, which are a subset of permissive tracts, and it is not used in the three-part form of mineral resource assessments. The lower map shows the strategy of moving inward from permissive rocks to delineate permissive tracts.

ferent people because of the difficulty of defining a commonly acceptable operational rule.

The preferred delineation strategy is to move inward from permissive rocks (fig. 1). Known deposits and occurrences serve to identify and expand permissive tracts, not constrain them. By using this definition, it is possible to subdivide a permissive tract into two or more parts that have different kinds of information, different numbers of undiscovered deposits, or possibly different amounts of uncertainty about the number of deposits.

Tracts may or may not contain known deposits. Areas are excluded from these tracts only on the basis of geology, knowledge about unsuccessful exploration, or the presence of barren overburden exceeding some predetermined thickness. A geologic map is the primary local source of information for delineating tracts and identifying which areas are permissive for different deposit types. Probably the second most important kind of information is an inventory of known mineral deposits and occurrences in and near the region being assessed. Because of incomplete deposit descriptions, it often is difficult to identify deposit types for many occurrences and some deposits, but those that can be identified increase confidence in tracts delineated for the deposit type. Occurrences may indicate the possibility of some deposit types and place limits on the kinds and sizes of deposits elsewhere. The map of deposits classified by deposit type then serves as a check on the accuracy of the delineation of tracts permissive for that type rather than a determinant of the delineation. Geochemistry of stream sediments may suggest deposit types and aid delineation of tracts for some deposit types. Geophysical surveys contribute by identifying extensions of permissive rock units under cover and identifying rock units in poorly mapped areas; in some cases, geophysical data can identify favorable rock units, such as hydrothermally altered rocks. Both stream sediment and rock geochemistry can provide similar benefits to large regional assessments.

Tracts are outlined for the possibility of the existence of one or more deposit types as inferred by analogy with deposits in similar geologic settings elsewhere. Mineral deposit models provide the means to make the links between geologic settings and deposit type. In every case, the boundaries of the tracts are based first on mapped or inferred geology. Original boundaries are reduced only where it can be firmly demonstrated that a deposit type could not exist. For some deposit types, extensive exploration can provide such evidence, but for many deposit types, only closely spaced drilling or overburden thicker than the delineation limit can be used to exclude areas.

Designation of a tract as permissive does not imply any special favorability for the occurrence of a deposit, nor does it address the likelihood that a deposit will be discovered there if it exists. Favorability for a deposit type is represented by the number of undiscovered deposits that are perceived to exist in a tract.

Estimation of the Number of Deposits

The third part of an assessment is the estimation of some fixed, but unknown, number of deposits of each type that exist in the delineated tracts. Until the area being considered is thoroughly and extensively drilled, this fixed number of undiscovered deposits, which could be any number including 0, will not be known with certainty.

Estimates of the number of deposits explicitly represent the probability (or degree of belief) that some fixed but unknown number of undiscovered deposits exist in the delineated tracts. As such, these estimates reflect both the uncertainty of what may exist and a measure of the favorability of the existence of the deposit type. Uncertainty is shown (fig. 2) by the spread of the number of deposits estimates associated with the 90 percent quantile and the 10 or 1 percent quantile; a large difference in the numbers suggests great uncertainty. Favorability can be represented by the estimated number of deposits associated with a given probability level or by the expected (mean) number of deposits.

Estimates are by deposit type and must be consistent with the grade and tonnage model and not with the population of mineral occurrences or weak manifestations of an ore-forming process (Singer, 1994a). Thus, the estimated number of deposits must match the percentile values of the grade and tonnage model. For example, for any estimate, approximately half of the estimated undiscovered deposits should be larger than the median tonnage and about 10 percent of the deposits should be as large as the upper 10 percent of the deposits in the tonnage model. If the grade and tonnage model is based on district data, then the number of undiscovered districts should be estimated. Some mineral deposit models, such as kuroko massive sulfide deposits, were constructed with spatial distance rules such as a 500-meter rule for combining mineralization—the same rule must be applied when the number of undiscovered deposits is estimated. Deposits in the study area that have published grades and tonnages are counted as discovered deposits, whereas those without published estimates are counted as undiscovered to avoid double counting.

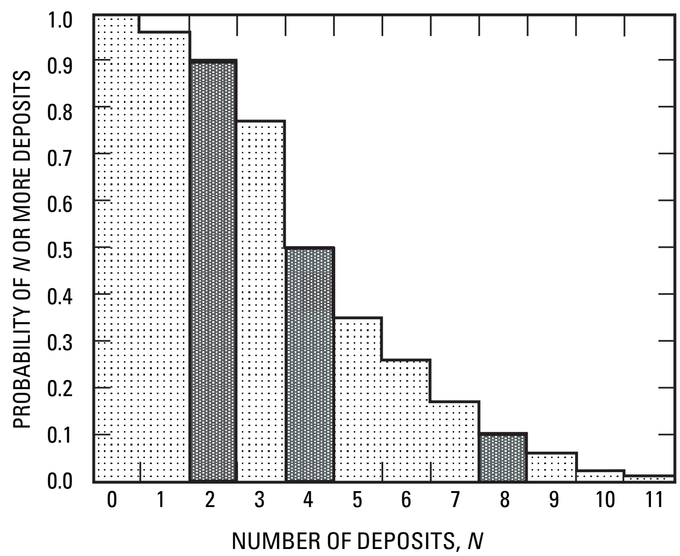

Figure 2. Graph showing three estimates (dark bars) of the number of undiscovered deposits along with interpolated values (light bars). The estimates were made at the 90, 50, and 10 percent quantiles. A large difference in the estimates at 90 and 10 percent would suggest great uncertainty, but this graph shows a relatively small difference.

Guidelines for Estimates

There are no fixed methods for making estimates of the number of undiscovered deposits. On the basis of experience and logic, however, at least seven different ways can be used directly or as guidelines to make these estimates (table 1). Each guideline represents some form of analogy. Most robust of these is a form of mineral deposit model wherein the number of deposits of each type per unit area from well-explored regions (Bliss and Menzie, 1993; Singer and others, 2001, 2005) is counted and the resulting frequency distribution is

Table 1. Guidelines for estimation of the number of deposits.
[Modified from Singer, 1993]

Guideline	Example	Reference
Frequency of deposits from well-explored areas	1. U.S., Alaska 2. Western U.S. 3. Costa Rica 4. Venezuela 5. Australia 6. General	1. MacKevett and others, 1978 2. Drew and others, 1986 3. Singer, 1994b 4. Cox, 1993 5. Scott, 2000 6. Bliss and Menzie, 1993
Local deposit extrapolations	1. U.S., Alaska 2. U.S., Alaska 3. Japan	1. Singer and MacKevett, 1977 2. Root and others, 1992 3. Kouda and Singer, 1992
Counting and assigning probabilities to anomalies	1. U.S., Alaska 2. Puerto Rico	1. Reed and others, 1989 2. Cox, 1993
Process constraints	1. Worldwide	1. Drew and Menzie, 1993
Relative frequencies of related deposit types	1. Worldwide	1. Drew and Menzie, 1993
Area spatial limits	1. Worldwide	1. Singer and Mosier, 1981
Total known metal	1. U.S.	1. Singer, 1993

used either directly for an estimate or indirectly as a guideline in some other method. Although Allais (1957) used this method of estimating the number of undiscovered deposits, many kinds of deposits were mixed together in his analysis.

In most three-part assessments, the final estimates were made subjectively, and many estimators used one or more of the above methods as guidelines. For example (see Singer and others, 2001), in the State of Nevada there are seven known deposits that are defined in the same way as deposits in the porphyry copper descriptive and grade and tonnage models. The tract permissive for all pluton-related deposits, including porphyry copper, covers about 41 percent of the area of the State (Cox and others, 1996). The well-explored, exposed permissive rocks in Nevada cover an area of about 32,800 square kilometers; five of the known porphyry copper deposits are in this exposed region. Areas covered by more than 1 kilometer of overburden are excluded from consideration. Concealed permissive areas within 1 kilometer of the surface are about 84,500 square kilometers in extent. Two of the known porphyry copper deposits are completely covered by younger materials and cannot be considered to belong to the population of deposits that are well explored and exposed.

If we assume that there are no additional porphyry copper deposits to be discovered in the exposed plutons in Nevada, then 5 deposits per 32,800 square kilometers (exposed permissive area) equals 0.00015 porphyry copper deposits per square kilometer. We can use this density of deposits to estimate the expected (mean) number of undiscovered porphyry copper deposits in Nevada. Thus, 0.00015 porphyry copper deposits per square kilometer times 84,500 square kilometers of covered permissive area equals an expected 12.9 concealed deposits; subtracting the 2 discovered deposits leaves 11 undiscovered concealed deposits that are defined in the same way as the deposits in the porphyry copper grade and tonnage model. For comparison purposes, the subjective estimate of the number of undiscovered porphyry copper deposits in Nevada by Cox and others (1996) is 8.7 deposits.

In an unpublished example, four scientists (participants A–D) made subjective probabilistic estimates of the number of undiscovered hot-spring mercury deposits in a 1:250,000-scale quadrangle in Alaska. They made independent estimates at the 90th, 50th, and 10th complementary percentiles (table 2). The estimate at the 10th percentile, for example, is the number of deposits for which there is at least a 10 percent chance of that number of deposits or more. It was pointed out to participant D that, because the number of deposit estimates must be consistent with the grade and tonnage model, his estimates imply that there is more undiscovered mercury in this quadrangle than has been found in the world in this deposit type. He replied that he was estimating wisps of cinnabar, not deposits consistent with the grade and tonnage model. In this case, knowledge of the total known amount of metal provided a guide to a flawed estimate. Using a variety of different guidelines for estimates provides a useful crosscheck of assumptions that may have been relied upon.

Table 2. Independent estimates by four scientists (A, B, C, and D) of the number of undiscovered hot-spring mercury deposits in a quadrangle in Alaska.

Percentile	Estimates by participant			
	A	B	C	D
90 percent chance of at least the number of deposits listed	1	1	2	9,000
50 percent chance of at least the number of deposits listed	3	2	4	10,000
10 percent chance of at least the number of deposits listed	6	6	7	11,000

Estimation Strategies

In practice, a small group of scientists who are knowledgeable about the deposit type (and advised by the regional experts) typically make consensus estimates. Two general strategies tend to be used (Menzie and Singer, 1990). In one, individual occurrences, prospects, and indicators are assigned probabilities, and the results are combined. In the other, the estimator recalls from experience many other areas that are geologically similar to the area being assessed and are well explored and uses the proportions of undiscovered deposits in these other areas to make the estimates for the new area. In each case, the scientists must weigh the geoscience and exploration information. A number of the guidelines for making these estimates listed in table 1 were used by a team estimating undiscovered resources in Nevada (Cox and others, 1996). Some estimators used the number of known deposits per unit area of exposed permissive rocks multiplied by the area of permissive rock concealed by less than 1 kilometer of overburden (postmineralization rocks and sedimentary deposits), as in the above example of porphyry copper deposits. Some based their estimates on the number of deposits known in well-studied areas of similar geology elsewhere in the world. Others depended on the number of occurrences that might become deposits as a result of more complete exploration, and still others were influenced by the number of exploration “plays” that could be visualized for the deposit type in question. Until more estimation guidelines and density of deposits models are available, it seems prudent to rely on mineral deposit specialists to make subjective estimates because they can bring their experiences and observations to the process.

Subjective probabilities such as those used here variously have been called degrees of belief or propositional probabilities. Geologists commonly make similar estimates that, although not explicitly quantitative, are subjective and have uncertainty, such as making geologic cross sections. Examples from different fields of study (Murphy and Winkler, 1984; Stern, 1991) demonstrate that, under some conditions, subjective estimates can be unbiased and reliable. The decades of experience of subjective and objective forecasting in meteorology provide insight into how the process of making subjective assessments in mineral resources might be improved. Murphy and Winkler (1984) found that consensus schemes performed better than almost all individual forecasters and that the best forecasts were made when objective forecasts were part of the information supplied to subjective forecasters. Among their recommendations were more effective use of many information sources, motivation to encourage forecasters to improve their performance, provision of formal procedures to assist forecasters in quantifying their uncertainty in terms of probability, and quick and extensive feedback concerning performance. Quick and extensive feedback might be difficult to apply in mineral resource assessments, except possibly through training exercises.

Sensitivity analysis shows that the greatest opportunity for reducing uncertainty in exploration and resource assessment lies with lowering the uncertainty associated with tonnage estimates (Singer and Kouda, 1999). Consequently, selection of the proper grade and tonnage model is probably more critical to the final assessment than small errors in estimates of the number of deposits.

Conclusions

The goal of many assessors is to make unbiased quantitative assessments in a format needed in decision-support systems so that the consequences of alternative courses of action can be examined. Internally consistent descriptive, grade and tonnage, deposit density, and economic models and the design of three-part assessments reduce the chances of biased estimates of the undiscovered resources. Biases can be introduced into these estimates either by a flawed grade and tonnage model or by the lack of consistency of the grade and tonnage model with estimates of the number of deposits.

Estimates of the number of undiscovered deposits explicitly represent the probability (or degree of belief) that some fixed but unknown number of undiscovered deposits exist in the delineated tracts. As such, these estimates reflect both the uncertainty of what may exist and a measure of the favorability of the existence of the deposit type. Although there are no fixed methods for making estimates of the number of undiscovered deposits, guidelines to help make these estimates are available. Using a variety of different guidelines for estimates both provides a useful crosscheck of assumptions that may have been relied upon and significantly reduces the chances of biased estimates.

Until more estimation guidelines and deposit density models are available, it seems prudent to rely on mineral deposit specialists to make subjective estimates because the specialists can bring their experiences and observations to the process. This kind of activity is not unusual; geologists commonly make estimates that, although not explicitly quantitative, are subjective and have uncertainty, such as making geologic cross sections. Experience from meteorology suggests that consensus schemes perform better than almost all individual estimators and that the best estimates are made when objective estimates such as those from guides (table 1) are part of the information supplied to subjective estimators.

Sensitivity analysis shows that the greatest opportunity for reducing uncertainty in exploration and resource assessment lies with lowering the uncertainty associated with tonnage estimates. Consequently, selection of the proper grade and tonnage model is probably more critical to the final assessment than small errors in estimates of the number of deposits.

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