



Targeting Method of Estimating Number of Undiscovered Mineral Deposits

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Abstract Central to exploration or development planning for undiscovered mineral resources is estimating the number of undiscovered deposits. Estimates are of deposit types permitted by geology in delineated tracts. Internal consistency and well-explored deposits in grade–tonnage and mineral deposit density models reduce chances of biased estimates, allowing economic analysis. Regardless of estimation method, each deposit type needs a grade–tonnage model based on well-explored deposits. Local deposits are typed and tested to ensure the grade and tonnage model is representative of undiscovered deposits. Most assessments have been made by expert judgements. An advantage of expert judgement is that all information can be used. Another estimation method, deposit density, is based on 10 deposit types in 109 control tracts using median tonnages and tract areas to estimate the number of deposits. It is robust, with an R^2 over 90%, and can be applied to any deposit type in permissive tracts. A third way to estimate deposits is by targeting, which has had limited application because location indicators of each possible target must be available. Here, an artificial example using the targeting method on iron deposits is presented. For comparison, the deposit density method is presented. The targeting method tends to have a slightly higher expected number of deposits but a lower probability of having large numbers of undiscovered deposits than the density method. If a single local well-studied deposit considered representative of yet-to-be discovered deposits were used, results would be upward–biased tonnages and larger estimates of numbers of deposits than with a targeting method.

Keywords Quantitative assessments · Deposit density · Expert judgement · Representative deposits

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1 Introduction

Estimating amounts of undiscovered mineral resources in a region might be done by predicting amounts of metal that are yet to be discovered. One way to do that might be to select a local well-studied deposit considered to be representative of yet-to-be discovered deposits. This method is seriously flawed due to unaddressed economic and technological effects. It also ignores uncertainties and likely has an upward bias. Including economic and technological effects requires information about numbers of undiscovered deposits and their associated grades and tonnages.

These and other mineral resource problems have been addressed by a widely used process of estimating undiscovered mineral resources called the three-part form of assessments (Singer and Menzie 2010). This process requires the use of a number of integrated models. The three parts are delineation of tracts from a deposit type's geologic setting using descriptive models, grade and tonnage models, and probabilistic estimates of the number of undiscovered deposits by type. Examples of the three-part form of assessments include undiscovered porphyry copper deposits in South America (Cunningham et al. 2008), orogenic gold deposits (Lisitsin 2010), and volcanogenic massive sulfide deposits (Rasilainen et al. 2014).

Descriptive deposit models provide guidance for relating locally observed geologic information to deposit types in order to delineate permissive tracts. A descriptive model contains properties observable at the map scale of assessments. Grade and tonnage models are necessary parts of three parts of assessments. Their frequencies are models of statistical frequencies of average grades and tonnages of undiscovered deposits. Similarly, numbers of well-explored deposits in well-explored control tracts provide models of frequencies of the total number of deposits in permissive tracts.

Depending on the desired form of the final assessment, economic models may be needed in which grades, tonnages, mining methods and costs, and resource prices are integrated to estimate costs and values of the undiscovered resources. Clear definitions of mineral deposits and linked deposit sizes and grades are required to conduct economic analysis. When it is desirable, the estimates of number of deposits, grades and tonnages, and economic models can be integrated with Monte Carlo simulation (Root et al. 1992; Bawiec and Spanski 2009).

Three-part assessments are the only known form of mineral assessment that requires internally consistent descriptive, grade and tonnage, and density models of mineral deposits that are operationally defined. The internal consistency of the models provides a robust method for avoiding bias in assessment results.

Linkage of methods and models boosts the distinction of this form of assessment from others by explicitly providing uncertainties. Because the number of undiscovered deposits cannot be known with certainty, it is necessary to present the number of undiscovered deposits and their linked grade and tonnage estimates in probabilistic form if the resource estimates are to be useful to decision-makers.

Discussion of descriptive and grade and tonnage models is presented to provide the foundation for an overview of the necessary steps necessary to prepare for estimating the number of undiscovered mineral deposits by any method. Following the deposit definition, three possible ways to estimate the numbers of undiscovered deposits, expert judgement, deposit density, and target estimates, are discussed. This is followed

by an example of estimating the number of undiscovered iron deposits in a tract using the density and the targeting methods. Finally, conclusions and recommendations about uses of these methods are presented.

2 Descriptive and Grade–Tonnage Mineral Deposit Models

Counting mineral deposits appears to be simple, but most mineral deposits do not have sharp boundaries and typically have heterogeneous internal grades. Many are only partly exposed or explored. Additionally, deposit information evolves over time. Knowledge about a deposit comes from exploration, mining, map-scale reports, and its ownership history. These factors can appear to change the name and tonnage and grades of a deposit. Some deposits have been mined by several companies and are reported as if they were separate deposits. Not uncommonly, two mines are located close in space with possible mineralization between them. Unbiased information about grades, tonnages, and numbers of undiscovered deposits in assessed tracts requires consistent operational definitions of mineral deposits in descriptive, deposit density, and grade and tonnage models. Descriptive models provide the geologic settings of a deposit type to guide delineations and a description of the geologic characteristics of the deposits to classify local deposits. They guide delineation of tracts that are permissive for that type (Cox and Singer 1986).

Rules defining deposits are needed to account for map scales and for some deposits that have multiple names or separately reported tonnages. A spatial rule is needed for each deposit type to consistently define which, if any, nearby ore bodies should be combined. These rules affect models of tonnage and grades and also density of deposits models and consequently number of deposit estimates. Estimates of numbers of undiscovered deposits are significantly affected by the grade and tonnage model.

It is necessary to have or make a grade and tonnage model before estimating the number of undiscovered deposits in a tract. A set of well-explored deposits of the type being considered have their individual total production, reserves, and resources added to make the models. Deposits for these models are commonly from locations around the globe, because there may be too few local deposits for a reliable model. The frequencies become the models of frequency grades and tonnages of undiscovered deposits of the same type in appropriate assessed tracts (Singer and Menzie 2010).

3 Preparation for Estimation of Number of Deposits

Before estimating numbers of undiscovered mineral deposits in a region, known deposits in the region need to be classified into types. This process includes both the well-explored deposits and any prospects that can be classed into deposit types. New or previously prepared descriptive deposit models (Cox and Singer 1986) are key to this process. The models and the geology in an area are examined and compared to delineate settings called permissive tracts where deposits of the type being assessed could occur based on exposed and extrapolated geology. Assessments in tracts are limited to some prespecified depth of deposits. In many assessments, a depth of 1 km has been used, but any defined depth can be used. Appropriate grade and tonnage models

for the permissive deposit types in the area are identified. Before estimating the number of deposits, tonnages and grades of the known well-explored deposits in the assessed area that follow the deposit type's spatial separation rule should be statistically tested with a t test to make sure the grade and tonnage model is not significantly different from the local known deposits. Delineated tracts, prospects, and number of known deposits in the tract that are not significantly different from the grade and tonnage model and signs of deposits are basic input to estimating the number of undiscovered mineral deposits.

4 Expert Estimation of Number of Deposits

Expert estimation has been widely used to address many practical problems and has been well studied. In one technique of making expert estimates, the Delphi method, experts do not directly interact with each other (Meyer and Booker 2001). The anonymous estimates are collected by the leader and distributed to the estimators to allow their modification in the next round. This process can continue until a consensus is reached. For mineral assessments, the lack of interaction of the experts probably results in loss of valuable information. Tests of the Delphi method to estimate uranium resources reported by Harris (1984) showed that the expert geologists did not change their estimates in later rounds. This is a good example why the Delphi method is not used to estimate number of deposits in three-part assessments. Geologists tend to believe that they know the answer and do not change their estimates unless shown evidence why they should—information from fellow geologists can provide that evidence.

In most three-part assessments, estimation teams consist of experts in geochemistry, geology, and geophysics of the tract. These experts supplement knowledgeable deposit type economic geologists, and resource analysts who are experienced in resource assessments (Singer and Menzie 2010). There are experts in the local geology and other indicators of deposits, but only persons with experience with multiple examples of the assessed mineral deposit type should be making estimates of the number of deposits. Other experts in geology, geochemistry, and other features are key sources of local information that can help the estimators during the assessment. This approach for estimating the number of deposits relies on experts' mental frequency distributions of deposits in other regions with similar characteristics. Experts base their estimates on geological characteristics of the tract compared to the deposit type descriptive model as well as other factors such as the amount and distribution of exploration in the tract and known deposits and prospects in the tract.

Before estimation, appropriate guides should be presented to the estimators. The number of deposits estimated has significance only with respect to a specific grade and tonnage model. Without this control, one estimator might be thinking of the number of only very small deposits, while another might be thinking of a few large mineable deposits. The estimators should be told that about half of each number-of-deposit estimate should exceed the deposit type's median tonnage. If the estimators do not apply this guide, the estimates will almost certainly be biased toward small deposits. A second guideline is an estimate of the number of deposits made by a

mineral deposit density model. The team of experts make individual estimates of number of undiscovered deposits by type in each tract, discuss these estimates, and then reach a consensus of estimates. Commonly, the number of undiscovered deposits is the number in the permissive tract that will equal or exceed the 90, 50, and 10% levels. For example, there might be a 90% chance of three or more deposits. The expert teams should have been calibrated through training sets in the process by which estimates should be made, introduction of statistical guides such as deposit densities, and feedback implications of their estimates (Meyer and Booker 2001).

5 Density Estimates of Number of Deposits

Tonnages and grades of well-explored deposits are used as models of frequencies of tonnages and grades of yet-to-be discovered deposits, and numbers of these deposits in well-explored control tracts can also be used as models of frequencies of numbers of deposits in permissive tracts (Singer 2008). Mineral deposit density models start with well-explored control tracts where the known number of deposits is consistent with a grade and tonnage model and a descriptive model. To prevent biased estimates of number of undiscovered deposits, deposits counted in density estimates generated from control tracts are consistent with well-explored deposits in the grade and tonnage models. Prospects or incompletely explored deposits are not counted in density control tracts. Only well-explored parts of control tracts are included. Covered areas are typically not well explored and are therefore not included.

An advance in density models was made when all data from control tracts of 10 different deposit types including porphyry copper and volcanogenic massive sulfide type deposits were combined and tract areas and median sizes of deposits in the appropriate grade and tonnage model were used in a multiple regression equation. Over 90% of the variation in deposit density was predicted using these two variables in an analysis of 10 different deposit types from 109 control permissive tracts worldwide (Singer 2008). In other words, the area of the permissive tract and median tonnage of deposits in the tonnage and grade model can be used to predict the number of deposits, regardless of deposit type.

In the general density model, estimates of density were derived by regressing median tons of deposits (s) and geologically permissive areas (a) against density of deposits to make the 50th percentile estimate. The data were logged (base 10) so requirements of statistical tests were not violated. The following equations (Singer and Kouda 2011) can be applied to any deposit type.

$$\log_{10}(\text{Density}_{50}) = 4.21 - 0.499 \log_{10}(a) - 0.225 \log_{10}(s), \quad (1)$$

where Density_{50} is the 50th percentile estimate of deposit numbers per 100,000 km², a the geologically permissive area in km², and s is median tonnage in millions of metric tons.

For the density estimate at a 90% confidence level and an upper density estimate limit at a 10% confidence level,

$$\log_{10}(Density_{90}, Density_{10}) = (\log_{10}(Density_{50}) \pm 1.290 \cdot 0.3484 \cdot \sqrt{(1 + (1/109) + (3.173 - \log_{10}(a))^2 \cdot (-0.3292 - \log_{10}(t))^2 / (109 - 1) \cdot 2.615 \cdot 1.188)}) \tag{2}$$

where 1.290 is Student’s *t* at a 10% confidence level and 106 degrees of freedom, *t*₁₀, 106 df, 0.3484 is the standard deviation of deposit density given tons and area, 109 is number of control tracts, 3.173 is mean log area [km²] of control tracts, −0.3292 is the mean log tons [millions] in control tracts, 2.615 is the standard deviation of control tract log tons, and 1.188 is the standard deviation of control tract log areas. To convert density estimates to number of deposit estimates at the 10th, 50th, and 90th confidence levels, log density per 100,000 km² is adjusted for permissive tract size and scale

$$N\%ile = a/100,000 * 10^{(\log_{10}(Density\%ile))}, \tag{3}$$

$$\log_{10}E(N) = \log_{10}(N_{50}) + \left(((\log_{10}(N_{10}) - \log_{10}(N_{50}))/t)^2 \right) / 2. \tag{4}$$

The mean number of deposits is 10 to the power of log₁₀ *E(N)*. Estimates made using these density equations are of total number of deposits in tracts. The mean total number of deposits in a tract is the sum of known plus estimated number of undiscovered deposits. To estimate the number of undiscovered deposits, known deposits in a tract must be subtracted from the expected total number of deposits [Eq. (4)]. The expected numbers are additive, so to estimate the number undiscovered requires revising the total expected number by subtracting the known deposits to make a new expected number. The new expected number and the variance are used to estimate a new median and 10th and 90th percentiles. The regression variance is calculated as

$$\text{var}N = \left((\log_{10}(N_{10}) - \log_{10}(N_{50}))/t \right)^2. \tag{5}$$

Median estimates of number of deposits adjusted for number of known deposits are 10 to the power of

$$\log_{10}(N_{50}) = \log_{10}(E(N) - \text{known number}) - \text{var}N/2. \tag{6}$$

In Eq. (2), log₁₀(*N*₅₀) is used instead of *Density*₅₀ to make probabilistic estimates of the number of undiscovered deposits after adjusting for known deposits. These estimates are made using logarithms and assume a discrete lognormal distribution. The conversion of a continuous distribution back to discrete space requires a continuity correction factor where estimates of the probability associated with a discrete number such as 3 is computed as areas of the probability distribution of the normal curve between 2.5 and 3.5. Thus, the *P* (*x* = 3) for the discrete distribution is approximated by *P* (2.5 < = *x* < = 3.5) for the continuous normal distribution.

General mineral deposit density equations [Eqs. (1) to (6)] were successfully used in predicting the numbers of undiscovered orogenic gold deposits in Victoria, Australia (Lisitsin et al. 2014) and unconformity uranium deposits in Australia (Singer et al. 2018), and the number of undiscovered volcanogenic massive sulfide deposits in an Arctic mid-ocean ridge (Juliani and Ellefmo 2018). A study comparing density method estimates to 100 expert estimates demonstrated the value of mineral density estimates as part of assessments (Singer 2018).

6 Target Estimates

A third method of estimating the number of undiscovered deposits in a tract is to identify all sub-areas in the permissive tract that might represent potential deposits and to evaluate the probability that each of these “targets” actually represents an undiscovered mineral deposit based upon the geoscience characteristics of the “targets”. In the target method, all areas in the tract that might represent possible targets are evaluated and assigned a probability that each possible target represents an undiscovered deposit that is consistent with the well-explored deposits of the type considered.

This approach relies on identifying potential exploration targets for the type of deposit being estimated. This requires detailed information. In this case, individual targets can be compared to deposit models to evaluate the likelihood that they are deposits of the type being estimated. If the target identification method is used as the geologic basis for estimation, a frequency distribution can be formed from probabilities assigned to individual targets. For example, a region may contain three targets. One may exhibit many features associated with a particular deposit type but may not have been sufficiently explored to establish if it is, in fact, a deposit. The expert may believe that the probability of this target being a deposit is very high and assign it a value of 0.9. A second target may have some features of known deposits but may differ in some important aspect; the expert might assign a probability of 0.3 to this target. The third target may be inferred from weak geophysical properties of the deposit or associated rocks. In this example, the expert might assign the target a low probability (0.05) of being a deposit. Reed et al. (1989) provide an example of this method for tin deposits in Alaska. Another early use of this method was estimating undiscovered porphyry copper deposits in Puerto Rico (Cox 1993). Singer and Menzie (2010) discuss implications of using this method.

To demonstrate the targetting method, a hypothetical assessment of undiscovered sediment-volcanic Fe deposits in an 8,500 km² permissive tract is presented. A grade and tonnage model based on deposits located elsewhere was constructed. A spatial rule of combining all deposits with edges within 2 km of each other into individual deposits was used in the grade and tonnage model. The median tonnage of these deposits is 4.9 Mt. The permissive tract in this example contains four well-explored deposits which are counted as known deposits. The tonnages of the four known deposits were tested and found to not be significantly different from those in the grade and tonnage model. All possible deposits are believed to have identifiable magnetic signatures, and all magnetic patterns within 2 km of each other were combined into individual possible deposits so that numbers of deposit estimates are consistent with the grade and

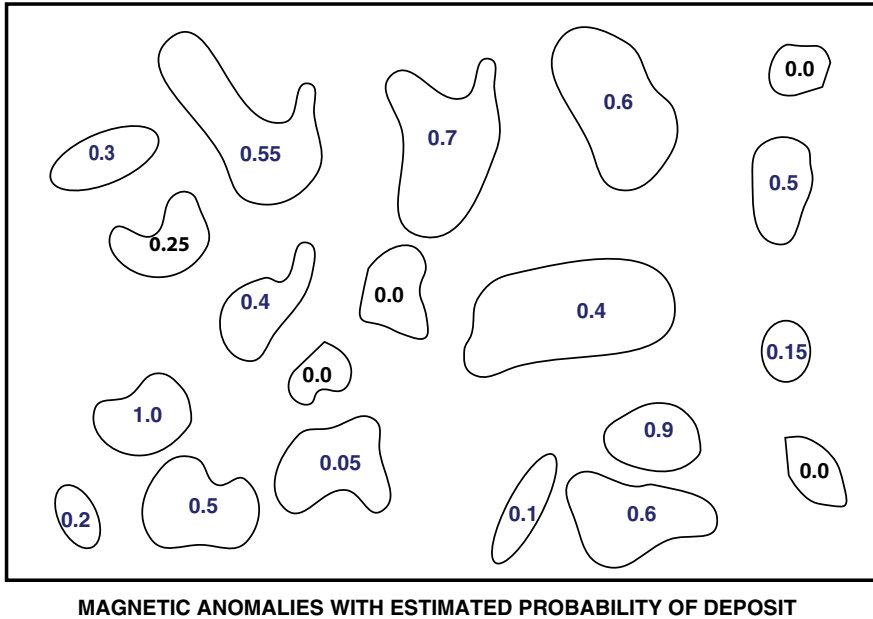


Fig. 1 Probability estimates that each magnetic anomaly represents an undiscovered Fe deposit. Expected number of deposits is the sum of anomaly probabilities = 7.2

tonnage model. The assessment is limited to the maximum depth of known deposits, the magnetic anomalies, and the permissive rocks in the permissive tract.

Two experts made estimates of the probability that each potential target had one yet-to-be discovered deposit (Fig. 1). All identified targets were within the permissive tract. The four well-explored deposits are assigned a probability of 0.0 because they have already been discovered and are explored (Fig. 1). The sum of the probabilities provides an estimated mean number of undiscovered deposits of 7.2 (Fig. 1). The total number of anomalies that are possible deposits is 20. But four of these represent discovered deposits, so the total number of possible undiscovered deposits cannot be above 16 by the requirement that all deposits be represented by an anomaly.

If the probabilities of the individual target deposits are mutually independent, the probability distribution of the number of deposits in the domain can be estimated by assuming that the estimates for each target are from a Poisson distribution. The sum of estimated probabilities in the tract is used to calculate the mean of the Poisson distribution. The sum produces the estimated mean number of undiscovered deposits of 7.2 using the targeting method (Fig. 1). The Poisson distribution allows us to estimate the probabilities of each possible number of undiscovered deposits. In this assessment, the Poisson distribution is used to provide a frequency distribution for undiscovered deposits. A Poisson distribution with a mean of 7.2 has a 90th percentile estimate of the number of deposits of three or more, a 50th percentile estimate of six or more, and a 10th percentile estimate of 10 deposits or more.

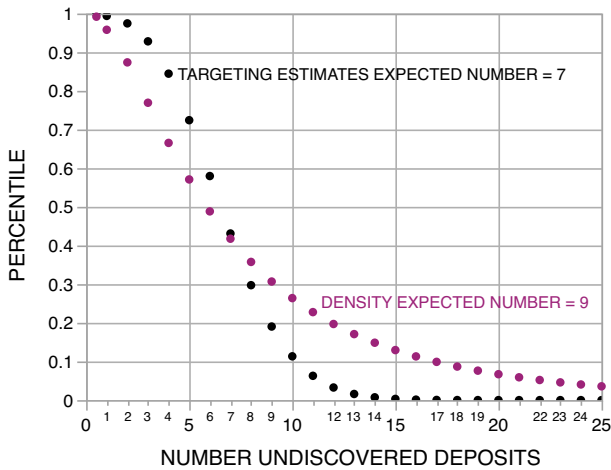


Fig. 2 Comparison of probabilistic number estimates of undiscovered Fe deposits by deposit density versus targeting Poisson methods

In this hypothetical example, it is possible to compare estimates of number of undiscovered Fe deposits made using the targeting method by expert judgement of potential targets to the estimates of the number of undiscovered deposits made with the general density model. In this example, the permissive area for sediment-volcanic Fe deposits is 8,500 km², and the median ore tonnage of the well-explored Fe deposits of the same type in the grade and tonnage model is 4.9 Mt. Using Eqs. (1) to (6) and adjusting for the four discovered well-explored deposits in the tract, the 90th percentile estimate is 2, the 50th is 6, and the 10th is 18 undiscovered deposits. The mean number of undiscovered deposits using the density method is 9 (Fig. 2). From Eq. (6), the median in log units is 0.80916, and the standard deviation is 0.3483 from the square root of Eq. (5).

Comparisons of estimates made by the two methods are shown in Fig. 2, where the probability of at least a certain number of undiscovered deposits is plotted against the probability of that number or more by method of estimation. In this example, the targeting method has a lower expected number of deposits and a lower probability of many deposits than estimates made by the density method. In general, the differences reflect underlying assumptions of the methods. With the Poisson distribution, it is assumed that the individual target deposits are mutually independent, whereas in the general density method it is assumed that there is some degree of clustering of targets.

7 Conclusions

Estimates of the number of undiscovered mineral deposits are critical information in decision-making about exploration programs and in consideration of land use. To be useful, the estimates need to be unbiased and account for the inherent uncertainty of any yet-to-be discovered deposits. These requirements are met by procedures used

in three-part quantitative assessments (Singer and Menzie 2010). Estimates are for specific deposit types that are permitted by the geology in delineated tracts of land. Each deposit type has a grade and tonnage model built on well-explored deposits in which spatial rules have been applied to combine close deposits into a single deposit. Grade and tonnage deposit data in models are commonly, but not required to be, from outside the permissive tract. These standards provide a robust basis for applying different methods of estimating number of undiscovered deposits.

Three methods of estimating the number of undiscovered deposits have been used in three-part assessments. Regardless of method, it is necessary to test the grades and tonnages of local well-explored and spatially separated deposits against the grade and tonnage model to make sure that the general model can provide unbiased estimates of the grades and tonnages of undiscovered deposits. This is necessary because the grade and tonnage model is also the model of grades and tonnages of the undiscovered deposits.

Most published three-part assessments rely on expert judgement (not the Delphi method) to estimate number of deposits. The primary advantage of the expert judgement method is that, if properly conducted, it can use all available information such as exploration history and adapt to information supplied by the local experts during the assessment.

A second method of estimating the number of undiscovered mineral deposits uses a density model based on frequencies of well-explored deposits in well-explored control tracts. This generalized deposit density model based on multiple deposit types simply uses the deposit type's median tonnage, the permissive tract's size, and the number of known deposits. It has been shown to be remarkably robust, with an R^2 of over 90% and applicable to any deposit type. Because of its generalization, it can be applied to any deposit type and in any properly defined permissive tract.

A third method, the targeting method of estimating number of undiscovered deposits, has had limited application because of the requirement that location indicators are present for every possible target. Thus, permissive tracts that include deposit types that could not be indicated by local information available could not be estimated. Where applicable, the targeting method is an effective way to estimate the number of undiscovered deposits. Here, an artificial example using the targeting method to estimate the number of undiscovered iron deposits is presented and compared to the deposit density method. The results were similar for the two methods. Differences reflect underlying assumptions of the methods. With the Poisson distribution, it is assumed that the individual target deposits are mutually independent, whereas in the general density method it is assumed that there is some degree of clustering of targets. The consequences of this assumptions are that the targeting method in this example has a slightly lower expected number of deposits and a lower probability of having large undiscovered deposits. In general, the density method will have a higher probability of a large number of deposits than that in the targeting method.

If instead of using the targeting or density methods, an assessment method using a single local well-studied deposit considered to be representative of yet-to-be discovered deposits were used, the results would be quite different. Tonnages of local representative deposits would quite likely be larger than other known deposits because they are more likely to be studied than small deposits. Therefore, an assessment using

this method would likely generate an upward-biased model of the tonnages of yet-to-be discovered deposits. It is also likely that the lack of a spatial rule would cause an overestimate of the number of undiscovered deposits. The combination of these two issues would produce much higher estimates of undiscovered resources than estimates from a properly conducted targeting method assessment, and there would be no way to estimate the considerable variability of undiscovered resources.

Experience in many three-part assessments suggests that if experts are available to make estimates, the best procedure would be to use the generalized density method to guide the experts' estimates. The experts could improve the density estimates based on local information such as local exploration or observations by the experts. Additionally, the density method can be used to identify any possibly flawed estimates that require further examination or justification (Singer 2018).

Experts could also identify any possibly flawed estimates and improve the density estimates based on local information such as local exploration or specific knowledge by experts. In less common situations where each possible undiscovered deposit has indicators that can have probabilities assigned, the targeting method along with the generalized density method is recommended.

Declarations

Conflict of interest The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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