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SPECIAL ISSUE

Methods of Three-part Quantitative Assessments of Undiscovered Mineral Resources: Examples from Victoria, Australia

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Abstract Quantitative mineral resource assessments following the 3-part form rely on grade and tonnage models and probabilistic estimates of the number of undiscovered deposits. Assessments completed in Victoria, Australia, indicate that undiscovered mineral resources can be effectively estimated using grade and tonnage sub-models constructed using only medium- and large-tonnage deposits. Numbers of undiscovered deposits can be estimated on the basis of expert judgement or entirely by statistical means. Appropriate mathematical aggregation of individual expert views, expressed at interactive expert workshops, provides robust estimates of the number of undiscovered deposits. Underestimation of uncertainty, which is common in expert judgement, can be compensated by the statistical modification of individual interval estimates. In this study, the linear opinion pool was used as a simple and robust method of mathematical aggregation of multiple expert estimates of the number of undiscovered deposits. A general regression model, which estimates numbers of undiscovered deposits based on the size of the geologically permissive area and the median deposit tonnage, provided results generally compatible with those based on expert judgement or local deposit density models.

Keywords Grade and tonnage model · Expert judgement · Mathematical aggregation · Number of undiscovered deposits · Orogenic gold

1 Introduction

Quantitative mineral resource assessments aim to provide unbiased probabilistic estimates of undiscovered resources. This information can be used by industry and government to make informed exploration, land use, and policy decisions (Singer

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and Menzie 2010; Scott et al. 2002). The focus of studies in Victoria, Australia, (Lisitsin et al. 2007, 2009, 2010a, 2010b) was to estimate the undiscovered gold endowment in northern parts of the Paleozoic Victorian gold province. This province has produced over 2500 t (80 Moz) of gold and hosts the giant Bendigo goldfield (>700 t Au) (Phillips et al. 2003). The northern part of the province is covered by Cenozoic sediments of the Murray Basin and remains poorly explored. Only a few gold occurrences have been discovered in this area. The assessments were restricted to orogenic gold deposits (Groves et al. 1998; Goldfarb et al. 2005; Moore 2007) and were conducted separately for the northern covered parts of the Bendigo, Stawell, and Melbourne structural zones of the Western Lachlan Orogen (VandenBerg et al. 2000; Gray et al. 2003; Champion et al. 2009). For the Bendigo and Stawell zones, quantitative estimates were made only for gold in mesozonal orogenic gold-quartz vein deposits, which dominate in that region. For the Melbourne Zone, quantitative estimates were made for gold in epizonal orogenic gold deposits characterised by refractory gold in quartz-pyrite-arsenopyrite veins and stockworks, or associated with quartz-stibnite-gold veins (Lisitsin et al. 2010a, 2010b). The northern covered part of the Bendigo Zone (10,000 km^2) is estimated to contain approximately 1,000 t (the mean) and at least 290 t (90% certainty) of gold in undiscovered mesozonal orogenic gold deposits (Lisitsin et al. 2007). For the covered area in the north of the Stawell Zone (30,000 km^2), the estimates are approximately 1200 t and at least 200 t of undiscovered gold (Lisitsin et al. 2009). The northern part of the Melbourne Zone (4400 km^2) is estimated to contain approximately 90 t, with a 90% certainty of 10 t of gold in undiscovered epizonal orogenic gold deposits (Lisitsin et al. 2010a).

The studies were based on the 3-part form of assessment of the United States Geological Survey (Singer 1993; Singer and Menzie 2010). This approach relies on grade and tonnage models to characterise undiscovered deposits and requires a probabilistic estimate of numbers of undiscovered deposits. The compilation of grade and tonnage models is usually complicated by problems of availability and quality of geological data; the estimation of the number of undiscovered deposits can be controversial, with no universally accepted methods. This paper suggests approaches that may assist with these latter two steps of quantitative mineral resource assessments.

2 Overview of the Method

The 3-part form of assessment assumes that mineral resources, contained in undiscovered deposits of a particular geological type, can be quantified using statistical distributions that characterise grades, tonnages and the spatial distribution of known deposits of the same type. Assessments are made separately for deposits of different geological types (deposit models) and include four major stages: (1) definition of permissive tracts where undiscovered deposits of a particular type may occur, (2) estimation of likely grades and tonnages of undiscovered deposits by an appropriate grade and tonnage model, (3) estimation of the likely number of undiscovered deposits, and (4) estimation of total undiscovered metal endowment.

The delineation of permissive tracts is based on geological criteria expressed in the appropriate descriptive deposit model. The boundaries of these tracts are defined such that the probability of any deposits of the particular model occurring outside the boundaries is negligible (Singer 1993). Likely variability of the grades and tonnages of undiscovered deposits is characterised by selecting an appropriate grade and tonnage model, constructed using data for a large number of well-explored deposits of the same type (Singer 1993). For many deposit types, global grade and tonnage models are available (Cox and Singer 1986; Bliss 1992). Where existing models do not adequately reflect the grade and tonnage properties of local deposits, quantitative assessments can use local grade and tonnage models, based on known well-explored deposits from within or near the assessment areas.

To ensure unbiased assessment results, exactly the same sampling unit (e.g. deposits, districts, ore fields) must be consistently used (Singer 1993). This requires an explicit definition of the selected sampling unit and the consistent use of this definition both in the construction of the grade and tonnage model and in the estimation of the number of undiscovered deposits (or ore fields, etc.). The sampling unit accepted for the assessments in Victoria was an ore field, defined as a group of adjacent orebodies that belong to the same deposit model and follow a spatial rule of being horizontally separated by less than 1.6 km (Lisitsin et al. 2007). Thus, orebodies less than 1.6 km apart were considered to be parts of the same mineralised system and their grades and tonnages were combined.

Each assessment area contains a fixed but unknown number of undiscovered deposits. In 3-part assessments, this number is estimated in a probabilistic form by a median and a credible interval, usually between the 10th and 90th percentiles. The number of deposits (n) estimated at a particular certainty level ($X\%$) indicates that there is an $X\%$ probability that the actual number of undiscovered deposits (N) is equal to or larger than n. Thus,

$$P(N \geq n) = X. \tag{1}$$

The estimates are typically based on subjective expert judgement, constrained by logical rules and the need for the estimates to be consistent with the grade and tonnage distribution. The expert estimates are often guided, or sometimes substituted, by statistical methods. A common approach is to use the number of deposits per unit area for one or several well-explored control areas (deposit density) as a guide for a geologically similar assessment area. The total number of undiscovered and discovered deposits can be estimated either by direct extrapolation or through regression by the size of permissive area if an appropriate regression model exists (Bliss and Menzie 1993; Singer and Menzie 2005, 2010; Singer et al. 2001; Singer 2008).

The final step in 3-part quantitative assessments is to estimate the undiscovered metal endowment and associated uncertainty through a Monte Carlo computer simulation that combines the grade and tonnage distributions with a probabilistic estimate of the number of undiscovered deposits. This simulation is typically performed using the MARK3 software (Duval 2000). The workings and logic of the MARK3 simulator are discussed in detail by Root et al. (1992) and in documentation supplied with MARK3 (Duval 2000).

3 Grade and Tonnage Sub-models of Significant Deposits

The larger mineral deposits account for the bulk of contained commodities for many deposit types (e.g. Laznicka 1983; Singer 1993, 1995). In the Bendigo Zone in Victoria and the Yilgarn Craton in Western Australia, over 99% of total gold production was from ore fields with more than 1 t of contained gold (Lisitsin et al. 2007). The dominance of larger deposits in total metal supply, as well as more reliable geological data usually available for these, suggests that grade and tonnage models based only on medium- to large-tonnage ('significant') deposits may be used to estimate undiscovered mineral resources. When 'significant' deposit grade and tonnage sub-models include a sufficiently large number of deposits (at least ten, preferably 20–30), their use does not radically affect estimates of total undiscovered resources, while simplifying the assessment process. For example, in the Bendigo Zone study (Lisitsin et al. 2007), the assessment of total undiscovered gold endowment was replicated following the same process to estimate numbers of undiscovered deposits, using the complete local grade and tonnage model and a sub-model of 'significant' ore fields. The latter were defined by an arbitrary lower cut-off of 0.8 t of contained gold. These simulations produced very similar distributions (Fig. 1, from Lisitsin et al. 2007). Their means differed by 10%, which can be explained by a downward bias in the method used to estimate the total number of undiscovered ore fields (including those with <0.8 t Au) consistent with the complete grade and tonnage model (Lisitsin et al. 2007).

More generally, total undiscovered mineral resources estimated by Monte Carlo simulation based on 'significant' grade and tonnage sub-models (only including deposits in the top 30–50% by contained metal) should approximate simulation results

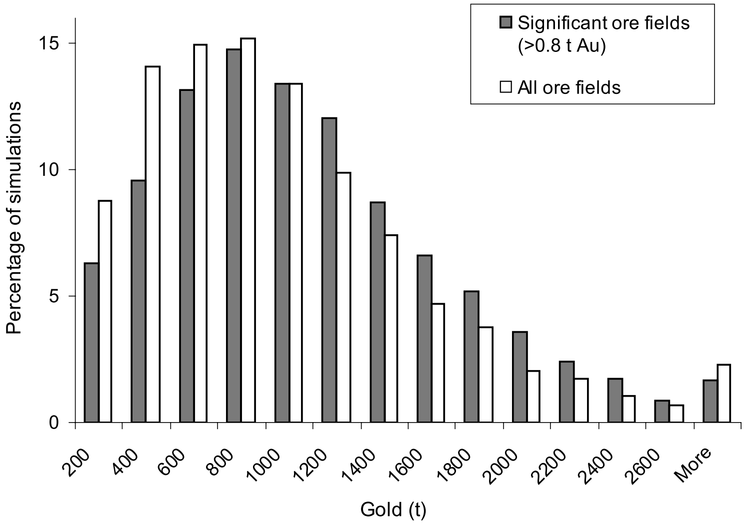


Fig. 1 Simulation results of the total undiscovered gold endowment in the Bendigo Zone, based on the complete grade and tonnage model (*white*) and a sub-model of significant ore fields (>0.8 t Au, *shaded*, from Lisitsin et al. 2007)

based on the corresponding complete models. However, this only holds true if the ratio of the expected number of undiscovered ‘significant’ deposits ($E(N_s)$) to the expected total number of undiscovered deposits ($E(N)$) is similar to the proportion of ‘significant’ deposits in the complete grade and tonnage model (n_s/n). Therefore, if

$$\big(E(N_s)/E(N) = n_s/n\big), \tag{2}$$

then

$$E(M) \approx E(M_s), \tag{3}$$

where $E(M)$ and $E(M_s)$ are the expected amounts of an undiscovered commodity simulated using a complete grade and tonnage model and a significant sub-model, respectively.

4 Estimating the Number of Undiscovered Deposits

The numbers of undiscovered deposits in the Victorian assessments were estimated by extrapolation of local deposit density in a well-explored part of the assessment terrain (Lisitsin et al. 2007) and by expert judgement (Lisitsin et al. 2009, 2010a). Principles of deposit density models are well documented (Bliss and Menzie 1993; Singer 1993, 2008; Singer et al. 2001; Singer and Menzie 2005, 2010), but the use of expert judgement requires further discussion.

4.1 Eliciting Expert Judgement

Subjective expert judgement has long been used in quantitative mineral resource assessments (Singer 1993) and other technical areas wherein obtaining objective data is impractical (Meyer and Booker 2001; O’Hagan et al. 2006). In the assessments for the Stawell and Melbourne zones (Lisitsin et al. 2009, 2010a), interactive expert workshops were deemed to be the best way to elicit expert estimates of likely numbers of undiscovered deposits. This elicitation environment can maximise the benefits of analysis and synthesis of individual experts’ knowledge through the group interaction. Research into different approaches for the elicitation of quantitative expert estimates indicates that using interactive expert groups can provide more accurate results than other approaches, such as individual interviews or the Delphi method (Meyer and Booker 2001; O’Hagan et al. 2006).

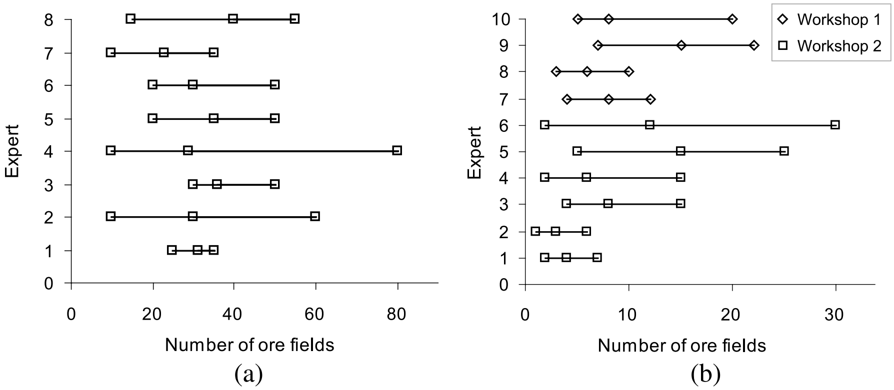
In the Victorian studies, mixed groups of experts, comprising six to ten specialists in regional and economic geology from government, academia, and industry, discussed the geological factors considered most likely to affect the number of undiscovered ore fields. The groups reviewed properties of local orogenic gold deposits and the boundaries of the geologically permissive tracts. The workshop participants then discussed the logical rules for the estimation of the number of undiscovered ore fields and some guidelines that could assist in the estimation process. The latter included deposit densities in well-explored parts of the assessment terrane and in similar areas in Victoria and globally.

The critical logical rule of the estimation explained to workshop participants was to maintain consistency between the estimated number of undiscovered ore fields at each certainty level and a selected grade and tonnage model of local significant ore fields. In particular, estimated numbers were only to include ore fields with over 0.8 t of contained gold. It was also explained to workshop participants that undiscovered ore fields may contain as much metal as any ore field in the grade and tonnage model. When estimating the number of undiscovered ore fields, experts considered that the proportion of undiscovered ore fields with ore tonnages above any given level was equivalent to the proportion of known ore fields above that level in the grade and tonnage model.

Workshop participants made individual estimates of likely numbers of undiscovered ore fields at three levels of certainty, described as the following: (i) median number ('best estimate,' equal chances of a higher or a lower number, 50% certainty N_{50}); (ii) lowest number (this number or higher is considered almost certain, 90% certainty N_{90}); and (iv) highest number (this number or higher is considered nearly impossible, 10% certainty N_{10}). The verbal descriptions and associated numeric probability values are consistent with the widely used Sherman Kent rating scale (see e.g. Meyer and Booker 2001, p. 115). No attempts were made to reach a consensus during workshops. Behavioural aggregation of individual estimates could substantially complicate the estimation process, introduce significant psychological biases, and underestimate uncertainty (Meyer and Booker 2001; O'Hagan et al. 2006). Instead, individual estimates (Fig. 2) were analysed and combined using statistical methods.

4.2 Analysis and Mathematical Aggregation of Expert Estimates

Individual expert responses (Fig. 2) do not show extreme cognitive biases in the estimation of the central tendency of the distribution of the number of undiscovered ore fields, but indicate occasional underestimation of uncertainty. This is par-



(a) (b)

Fig. 2 Individual expert estimates of the number of undiscovered ore fields for the Stawell Zone (**a**) and the Melbourne Zone (**b**). Medians and 80% intervals are shown. *Diamond* and *square* markers distinguish estimates made at different workshops ticularly obvious for responses 1, 3, and 7 (Fig. 2a). The underestimation of uncertainty bias is common for expert judgement. In particular, when experts estimate a range that would contain a correct value with a 90% probability, they often construct a much narrower 50–60% credible interval (Meyer and Booker 2001; O'Hagan et al. 2006). To gauge this possible underestimation of uncertainty, we evaluated coefficients of variations (CV) for individual expert estimates, assuming that 'best estimates' and credible intervals represent medians and 10th and 90th percentiles of some statistical distributions

$$CV = s/E, \tag{4}$$

where E is the expected number of undiscovered deposits and s is the standard deviation. Evaluating both E and s requires an assumption on the type of statistical distributions represented by expert estimates, and any choice would be difficult to substantiate. For this analysis, we selected an empirical 'distribution-free' MARK3 algorithm (Root et al. 1992; Singer and Menzie 2005). Singer and Menzie (2005) showed that, for porphyry copper deposits, this algorithm can produce estimates with intermediate relative variance, higher than that for the low-variance Poisson model and lower than that for the linear regression model. They recommended the MARK3 algorithm as a robust and easy-to-use method for evaluating alternative estimates of the number of undiscovered deposits.

Accordingly, expected numbers of undiscovered ore fields and standard deviations for individual expert responses were estimated using regression equations from Singer and Menzie (2005).

$$E = 0.233N_{90} + 0.4N_{50} + 0.225N_{10} + 0.045N_{05} + 0.03N_{01}, \tag{5}$$

$$s = 0.121 - 0.237N_{90} - 0.093N_{50} + 0.183N_{10} + 0.073N_{05} + 0.123N_{01}, \tag{6}$$

where N_{90}, N_{50}, N_{10}, N_{05} and N_{01} are estimated numbers of ore fields at the 90%, 50%, 10%, 5%, and 1% certainty levels, respectively. We further assumed that

$$N_{10} = N_{05} = N_{01}, \tag{7}$$

thus implying that the estimated number of ore fields at the 10% certainty level represents the highest value for each distribution. This essentially truncates distributions at the 90th percentile and gives slightly lower estimates of E, s and CV compared to MARK3 distributions with

$$N_{10} < N_{05} < N_{01}. \tag{8}$$

Low variances of several estimates ($CV < 50\%$) confirmed that some participants apparently underestimated uncertainty when they expressed their opinions on the number of undiscovered deposits numerically as credible intervals. The narrow intervals from the Stawell Zone study (Lisitsin et al. 2009) were inconsistent with the converging view of the workshop participants on the presence of very large uncertainties in prospectivity for the northern part of the Stawell Zone. This required modifications of low-variance estimates to better reflect underlying uncertainty while preserving the original views of experts on the 'best estimate' number of undiscovered deposits.

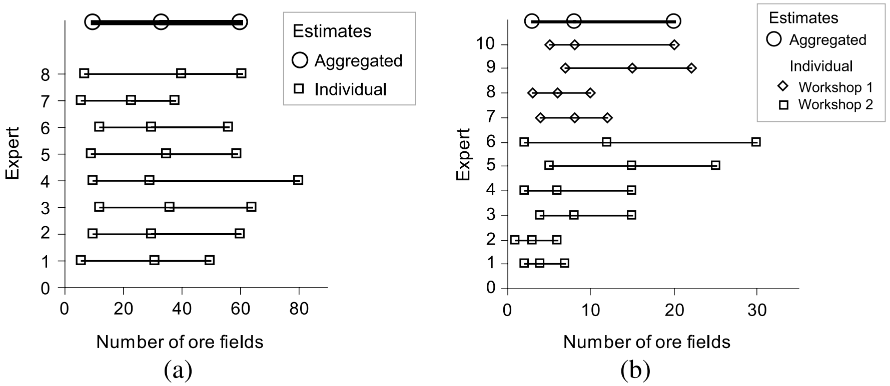


Fig. 3 Individual and aggregated expert estimates of the number of undiscovered ore fields: (**a**) Stawell Zone, and (**b**) Melbourne Zone. Aggregated estimates are shown by *thick lines* with round markers

Thus, N_{90} and N_{10} for low-variance intervals (Fig. 2a) were modified so that CV increased to an arbitrary level of 50% while E (5) and N_{50} remained unchanged (Fig. 3a).

Lisitsin et al. (2009, 2010a) combined individual intervals into a single distribution by simple equal weight linear pooling (Gedest and Zidek 1986; O'Hagan et al. 2006)

$$f(x)=\sum_{i=1}^{n} w_i f_i(x), \tag{9}$$

where n is the number of experts, $w_i = 1/n$ (equal weights given to all experts), and $f(x)$ is the probability of a particular value of the number of undiscovered ore fields x. This aggregation method was selected because of its simplicity and reported robustness (O'Hagan et al. 2006) and, importantly, because it preserves underlying uncertainty, expressed by individual expert estimates, better than many alternative methods. It was assumed that N_{90}, N_{50}, and N_{10} of individual expert estimates (with N_{90} and N_{10} modified to increase CV, if required) represent the 10th, 50th, and 90th percentiles of an empirical MARK3 distribution. Thus, for each set of expert estimates, $f(x)$ was evaluated for all integers between 0 and N_{10}, and individual MARK3 distributions were combined using (9) (Fig. 3).

4.3 Comparison with Other Aggregation and Estimation Methods

There are many alternative methods of mathematical aggregation of expert estimates. Also, the number of undiscovered deposits can be estimated entirely by statistical means. A comparison of estimates obtained using different approaches can indicate a degree of robustness of assessment results. Here we will only review several alternatives, with selected results listed in Table 1.

The logarithmic opinion pool (O'Hagan et al. 2006)

$$f(x)=k\prod_{i=1}^{n} f_i(x)^{w_i}, \tag{10}$$

Table 1 Estimates of the numbers of undiscovered deposits, obtained using different methods or assumptions. Original estimates are those from Lisitsin et al. (2007, 2009, 2010a, 2010b). $E(N)$ is the expected number of undiscovered deposits, evaluated assuming that the percentile values represent MARK3 distributions (5)

	Bendigo zone				Stawell zone				Melbourne zone			
	N_{90}	N_{50}	N_{10}	$E(N)$	N_{90}	N_{50}	N_{10}	$E(N)$	N_{90}	N_{50}	N_{10}	$E(N)$
Original estimates	15	25	32	23	10	33	60	34	3	8	20	10
Linear pool (uniform priors)					9	36	64	37	3	9	21	10
Monte Carlo (uniform priors)					18	35	52	34	6	9	12	9
General regression model	6	18	50	24	12	34	95	45	5	13	38	18

where k is a normalising constant ensuring that $f(x)$ integrates to 1, produces a narrow aggregated distribution, limited to an interval of overlap between all individual probability distributions. This either indicates unrealistically strong aggregated beliefs, or may result in $f(x) = 0$ for all values of x, which renders this aggregation method unsuitable. More complex Bayesian and opinion pooling methods using unequal weights for different experts are rarely used and are difficult to implement while not necessarily improving performance (Meyer and Booker 2001; O'Hagan et al. 2006).

Bootstrap and Monte Carlo simulations of medians only characterise uncertainty of medians (Meyer and Booker 2001) and thus produce relatively narrow credible intervals (particularly the bootstrap). However, Monte Carlo simulations can provide robust estimates of pooled medians (aggregated N_{50}) and a minimum measure of uncertainty. Results of Monte Carlo simulations of medians assuming the uniform distribution of expert estimates, as well as estimates from linear pooling assuming uniform priors, are therefore included in Table 1. Singer (2008) showed that the spatial deposit density of mineral deposits of any type can be estimated by regression using the size of the permissive area and the median of a tonnage model as the only parameters. This approach provides an alternative estimation method, totally independent of expert judgement and most assumptions accepted in the Victorian assessments. The median number of deposits per 100,000 km^2 of the permissive tract (deposit density, D_{50}) can be evaluated from

$$\log_{10}(D_{50}) = 4.21 - 0.5 \times \log_{10}(A) - 0.225 \times \log_{10}(T), \tag{11}$$

where A is the permissive area in km^2 and T is the mean of the log-transformed (base 10) tonnage distribution of the deposit model in question, in million tonnes (Singer and Menzie 2010, modified from Singer 2008). Deposit densities at the 90th and 10th percentiles can be estimated from the regression model of Singer and Menzie (2010, modified from Singer and Kouda 2008)

$$
\begin{aligned}
&\log_{10}(D_{90}, D_{10}) \\
&\quad = \log_{10}(D_{50}) \pm 0.449 \\
&\qquad \times \sqrt{1.009 + 0.029 \times \bigl(3.173 - \log_{10}(A)\bigr)^2 \times \bigl(-0.329 - \log_{10}(T)\bigr)^2}. \qquad (12)
\end{aligned}
$$

N_{10}, N_{50}, and N_{90} can then be estimated using solutions of (11) and (12) as

$$N_{10(50,90)} = A/100{,}000 \times 10^{\log_{10}(D_{10(50,90)})}. \qquad (13)$$

Solutions of (13), using input data from Lisitsin et al. (2007, 2009, 2010a) are included in Table 1.

Linear opinion pooling assuming the MARK3 and uniform distributions of expert estimates produced almost identical results. Monte Carlo simulations of medians provided very similar estimates of N_{50} and $E(N)$, but underestimated underlying uncertainty, as expected. The general regression model (Singer 2008; Singer and Menzie 2010) produced estimates close to those based on the mathematical aggregation of expert judgement (Lisitsin et al. 2009, 2010a). The regression estimates were also generally consistent with results of the extrapolation of local deposit density in the Bendigo Zone study (Lisitsin et al. 2007). In all three cases, the general regression model gave wider 80% confidence intervals which completely or mostly included the confidence intervals based on the original estimates (Lisitsin et al. 2007, 2009, 2010a). The overall similarity of the estimates of the number of undiscovered deposits obtained using different assumptions and independent methods suggests that estimates based on reliable local deposit density models (Lisitsin et al. 2007) and mathematically aggregated expert judgement (Lisitsin et al. 2009, 2010a) can be robust.

5 Discussion

Quantitative estimates of undiscovered mineral resources are dominated by the properties of a relatively small number of large deposits in grade and tonnage models. This fact can be used to justify the generation and use of sub-models based only on ‘significant’ (medium- to large-tonnage) deposits. Such sub-models need to include a reasonably large number of deposits (at least ten, preferably 20–30) to adequately reflect the natural variability of deposit grades and tonnages. The use of ‘significant’ grade and tonnage sub-models can substantially simplify the process of quantitative resource assessments and interpretation of assessment results. However, the general application of significant’ grade and tonnage sub-models needs to be further investigated for other deposit types.

Guided expert judgement, elicited during interactive workshops involving five to ten participants and followed by mathematical aggregation of individual expert views, can provide robust estimates of the number of undiscovered deposits. Common underestimation of uncertainty by experts may require statistical modifications of individual estimates. The linear opinion pool is a simple and robust method of mathematical aggregation of probabilistic expert estimates.

The general regression model (Singer 2008; Singer and Kouda 2008; Singer and Menzie 2010) can be used as a convenient tool to estimate the number of undiscovered deposits or to validate estimates obtained by other methods. As indicated by the reviewed examples, the general model can be expected to give estimates with higher variance compared to specific local models. This may reflect inherent higher uncertainty of the general model, which is based on 10 different deposit types from 109 control areas worldwide. Alternatively, the higher uncertainty indicated by the general model can be interpreted as a more stable measure of the natural variability of deposit densities in different metallogenic provinces.

For some assessment areas (e.g. large, poorly explored parts of richly endowed metallogenic provinces under post-mineralization cover), estimated numbers of undiscovered deposits, consistent with a local grade and tonnage model, may imply the presence of more than one giant deposit in the same province. However, many well-explored metallogenic provinces only have a single giant deposit. An explicit decision on a geological possibility of multiple giant deposits of the same type in the same geological terrane can dramatically affect quantitative estimates of undiscovered mineral resources. This should be considered when interpreting assessment results for the Bendigo and Stawell zones (Lisitsin et al. 2007, 2009).

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