AN OVERVIEW OF THE ESTIMATION OF KIMBERLITE DIAMOND DEPOSITS

D Bush
ZStar

Abstract

The nature of diamond deposits are such that most mineral resource reporting codes contain a sub-section unique to diamond estimation and classification. These codes identify a number of criteria which define the uniqueness of diamond deposits, including, the low and variable grade of diamond deposits; the particulate nature of diamonds which affects both size and revenue of individual particles and finally the inherent difficulties and uncertainties in the estimation of diamond resources.

These criteria are expanded on to provide an overview of the estimation of kimberlite diamond deposits. Placer deposits have been excluded as they constitute a particularly complex example of particulate distributions.

Diamond grade, typically of the order of parts per million (ppm), is dependent on the number of stones per unit volume or mass as well as the diamond size distribution while diamond revenue is dependent on size, model, colour and quality. These parameters of a discrete particle result in a commodity which requires some unique estimation and modelling methodologies. For most commodities "grade" is a measure of concentration and is directly proportional to value. In the case of diamonds however the same stone grade (e.g. stones per 100 tonnes) may have significantly different carat grades and revenue, depending on the characteristics of the individual stones (size, model, colour and quality).

The De Beers Consolidated Mines Venetia Mine is used as an example of diamond estimation as well as to highlight some propriety grade estimation techniques. The mine has been sampled for grade using a number of different sample supports, from 36" diameter reverse circulation drillholes to micro diamond core drilling. De Beers Group Services (Pty) Ltd (DBGS) have developed a technique of mixed (or multiple) support kriging which allows for the combination of samples of different sizes (and therefore grade distributions) in the estimation process.

In addition DBGS have researched techniques of both global and local grade estimation using micro diamonds.

The estimation of kimberlite diamond deposits has a number of unique components resulting from the discrete nature of the diamond distribution. It is however equally fundamentally important to understand exactly what the sampling data represents; the constraints under which the data were collected (e.g. bottom cut off) and the adjustments necessary to ensure parity

between and within sampling programmes as well as the likely metallurgical process in a production environment.

1. Introduction

Diamond deposits and the estimation thereof, both kimberlitic and placer, are considered sufficiently unique to warrant a sub-section in most reporting codes; e.g. the JORC Code clauses 40 to 43 and the SAMREC code clauses 54 to 62. These codes identify a number of criteria which define the uniqueness of diamond deposits, including:

- The low and variable grade of diamond deposits
- The particulate nature of diamonds, i.e. discrete rather than continuous distributions
- Diamonds occur in different sizes with a particular distribution which affects both grade and revenue
- Diamond value is not unique but depends on size, model, colour and quality
- The inherent difficulties and uncertainties in the estimation of diamond resources and reserves.

(SAMREC, JORC, CRIRSCO)

These criteria form the basis for an overview of the processes involved in the estimation of kimberlite diamond deposits. Placer diamond deposits have been deliberately excluded from this review as they constitute a further level of complexity, particularly in terms of content and mineralisation models (see Figure 1).

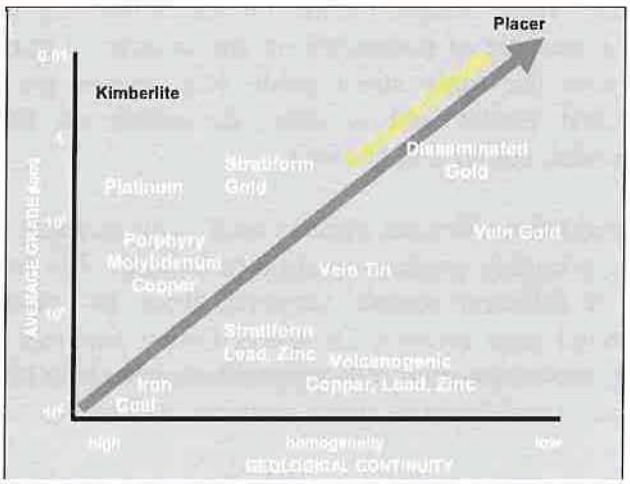

Figure 1 Estimation complexity as a function of grade and geology. (after King, et.al., 1982)

For most kimberlite pipes grade is expressed in terms of carats per unit volume or mass. For mass the norm is carats per tonne or 100 tonne (cpht). As 1 carat is 0.2 grams a grade of 50cpht

equates to 0.1ppm or 0.00001%. The carat grade value itself is an "accumulation", i.e. the combination of two variables – diamond content or stones per m^3 and stone size or carats per stone. If grade is expressed in terms of tonnes a third variable is introduced namely density. Stone grade distributions are typically positively skewed (a high grade "tail" to the distribution) and frequently follow a lognormal distribution.

Diamond grade is therefore dependent on the number of stones per unit volume or mass and the diamond size distribution while revenue is dependent on size, model, colour and quality (Figure 2). It is these consequences of a discrete particle that make diamond mineral resource estimation more complex than most other commodities. There is no unique value for diamond revenue; in fact, two deposits with the same stone grade may well have different carat grades and average revenue. Diamond size is typically described in terms of a size frequency distribution which lists the number of stones within particular size classes. Size frequency distributions, like grade, are typically lognormal with a long positive tail. References to average stone size should always be accompanied by a stated bottom cut off. The size class can be according to standard sieve sizes, e.g. DTC (Diamond Trading Company) or Antwerp, carater / grainer intervals or simply mm sizes.

Figure 2 Diamond assortments; model, colour and quality

Diamonds are sub-divided into numerous categories for valuation purposes; the DTC for example has well over 10 000 different categories or price book items. For revenue estimation purposes the categories are normally aggregated into sizes according to the size distribution, be it sieve sizes or a sieve size - carater / grainer combination. The value per size category is thus weighted by the size distribution to arrive at an average price. As revenue is influenced by size

an average price should be qualified by a stated bottom cut off and care must be taken that this correlates with the quoted grade values.

The low grades of diamond deposits typically necessitate the collection of large sized samples for grade and revenue estimation. A sampling optimisation exercise can be highly beneficial in terms of cost and information and should be undertaken prior to an extensive and expensive sampling programme. The optimisation exercise should encompass both sample support size and sample spacing parameters. Depending on the grade and size distribution as well as the objective(s) of the sampling programme drillhole diameters utilised can be up to 36" (Figure 3). Once again the discrete particle nature of diamonds affects the sampling process in that the recovery methodology should optimise diamond liberation while minimising diamond damage. The *carat* grade estimate is reliant on optimal diamond liberation (above the desired bottom cut off) while the *stone* grade estimate is dependent on minimal diamond damage. Similarly the revenue estimate is influenced by the size distribution thus optimal liberation without damage is important. In addition the assortment (model, colour and quality) and the model or shape, in particular, requires minimal diamond damage.

Figure 3 Large diameter drillhole tri-cone bit with macro diamond recovery

A multi-phase sampling strategy is not uncommon in exploration where further work is dependent on positive results. However multiple phases in diamond sampling can generate significant integration issues if the sampling and recovery methodologies are different. For example combining programmes with different drilling configurations (e.g. percussion vs. tri-cone bits) or recovery processes (single vs. multiple phase comminution) will generate different diamond liberation / lockup and damage characteristics. Failure to address these differences will result in biased sampling and sub-optimal grade and size frequency distribution estimates.

The geostatistical approach to kimberlite diamond resource estimation is well established and follows fairly standard methodologies. However the key to diamond grade estimation is correct or optimal decisions prior to the process, critical areas for consideration are:

- the appropriate variable for estimation (stone or carat grade; volume or mass units etc)
- the incorporation of calliper data for sample volume and density for sample mass
- the bottom cut off and the inclusion or exclusion of incidental diamonds
- the modifications necessary to combine different data sources or address different recovery processes, liberation / lockup profiles etc.

A further complication to grade estimation is the necessity to adjust the resource grade and size frequency distribution (and therefore revenue) to address the likely production plant recovery process. A main treatment plant with staged comminution, multiple stream recovery passes and recrush circuits is likely to have a different overall recovery than the sample plant on which the resource estimates are based.

The application of micro diamonds (<0.5mm) in grade estimation has been well known for some time and has numerous advantages over conventional sampling, not least of all in time and cost savings due to the smaller support size required (Figure 4). Recent research has improved the application of the technique so that local (block) grade estimates can be calculated using a geostatistical approach. A further output of micro diamond data is the so called "total content curve" size frequency distribution. This size distribution is assumed the closest to the in-situ distribution of diamonds within a kimberlite because comminution is kept to a minimum and the total chemical dissolution is akin to 100% diamond liberation. This distribution is used in grade and revenue estimation as well as geo-metallurgical applications (granulometry, particle size distributions and process efficiency)

Figure 4 Micro diamond core and recovery

A further enhancement to the estimation of diamond grade involves the use of different sample sizes in local grade estimation. These different samples (e.g. large diameter drillhole and bulk samples) can be combined geostatistically to optimise all available data for estimation purposes.

The estimation of kimberlite diamond deposits has a number of unique components resulting from the discrete nature of the diamond distribution. It is fundamentally important to understand exactly what the sampling data represents; the constraints under which the data were collected (e.g. bottom cut off) and the adjustments necessary to ensure parity between and within sampling programmes. Finally the estimated grade and revenue should conform to the likely recovery efficiency of the planned "production" metallurgical process.

A case study has been used to highlight the estimation methodology, and potential pitfalls, of kimberlite pipe diamond estimation. This study is not intended as a recipe for diamond grade estimation but rather to highlight areas of grade estimation which require particular attention and understanding.

2. A De Beers case study – Venetia mine

The De Beers Consolidated Mines Venetia mine is presented as the case study. The mine is located some 80Km west of Musina in the Limpopo Province of South Africa. The mine has been in production since the eighties and has been sampled, for grade, using various techniques. The initial cable tool drilling in the eighties was followed by the Advanced Sampling Programme (ASP) and Repeat Advanced Sampling Programme (RASP) in the mid nineties and the Resource Extension Programme (VREP) in 2006. These programmes were designed for macro diamond recovery. Micro diamond data were collected from the geological delineation drilling and pilot core drilling which ran concurrently with the VREP. These micro diamond data were used to extend the grade estimates below the depths reached by the (R)ASP and VREP drilling.

The objective of the latest resource review was to integrate the macro and micro diamond sampling to extend the Indicated resource category of the mine at depth. The extent of the mine's Indicated resources was initially limited to the cable tool drilling which reached depths of some 200m. The combined (R)ASP and VREP drilling should extend the Indicated resource to at least 500m below surface.

2.1 Data

The ASP and RASP macro diamond sampling holes were drilled with a 12¼" diameter with samples collected in 12m lifts coincident with mining bench heights. The ASP drilling used tungsten button bits in a percussion hammer configuration while the RASP used a rotary tri-cone.

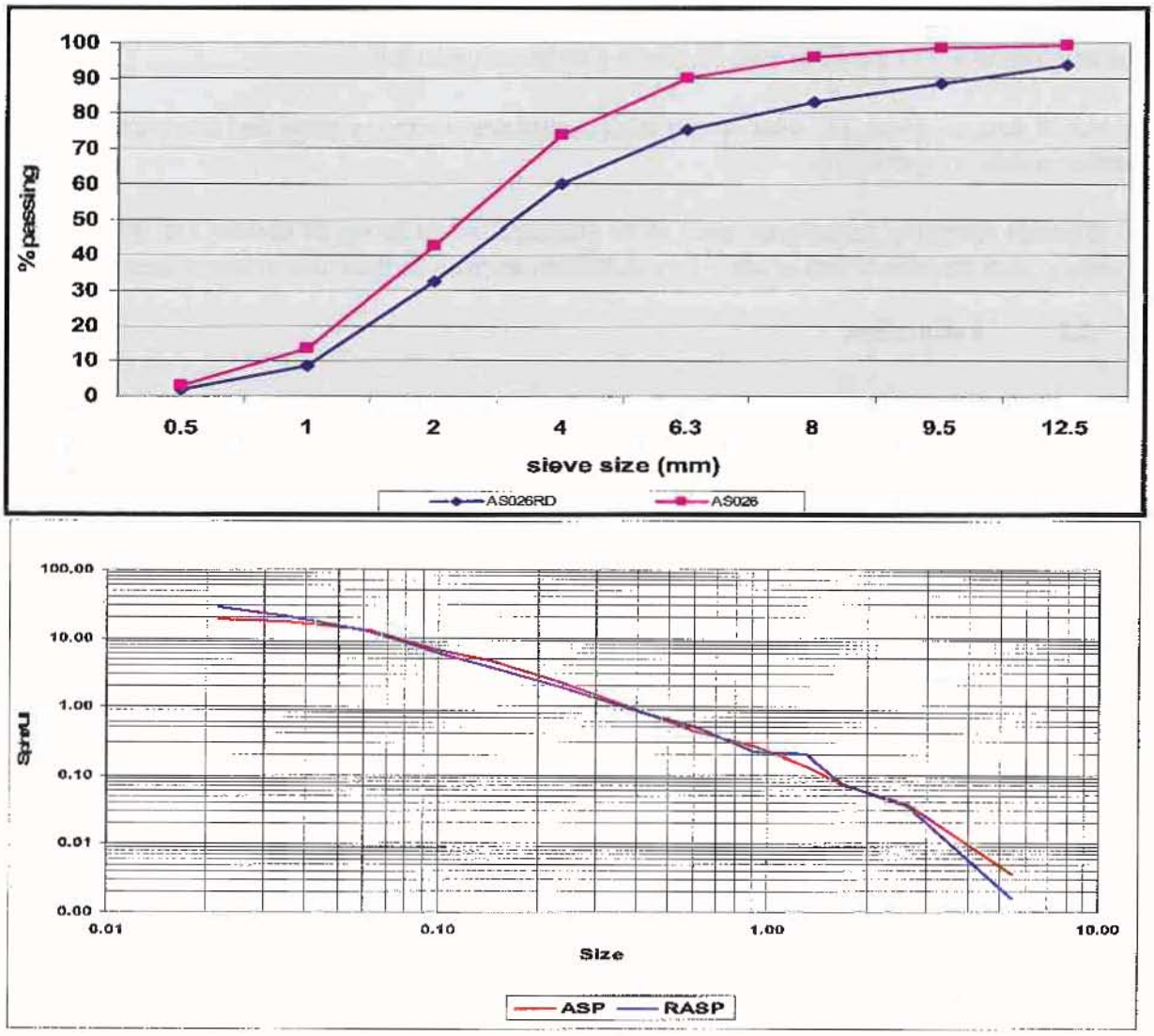

Figure 5 Particle size and diamond grade – size plot for ASP and RASP drilling in the same kimberlite facies at Venetia

Sample treatment was similar for both programmes; a 1.0mm screen at the drill site removed slimes while a closed circuit jaw crusher limited the top size of the material to 8mm. The DMS concentrate was subject to final recovery at the then Anglo American Diamond Research Laboratory (DRL) in Johannesburg.

The difference in drill bit (hammer vs. tri-cone) had a significant impact on the sample grade with the hammer drill causing diamond damage and a lower sample grade. This is shown in the particle size distribution (Figure 5) as well as a grade – size plot. The hammer clearly shows a finer particle size distribution which has resulted in a finer diamond size distribution and therefore diamond loss to underflow and an artificially lower diamond grade. The grade – size

plot indicates an over recovery in the mid sizes for the ASP data due to breakage in the coarser sizes and a shortfall in the finer sizes following losses to underflow.

The VREP data involves 23" diameter drilling, a different recovery plant and therefore a similar exercise in data compatibility.

The different sampling techniques need to be standardised in terms of bottom cut off, recovery efficiency, size frequency and grade – size distributions prior to their use in the estimation.

2.2 Estimation

For local block estimation purposes it is necessary to select (optimise) a suitable block size for estimation purposes. Bench height is often determined by mining, geotechnical and equipment criteria. Block dimensions in the horizontal plane are typically defined by the drill hole spacing. As a general rule block dimensions should not be less than half the drill spacing.

Grade estimation at Venetia was carried out using a combination of ordinary kriging, mixed (multiple) support kriging and micro diamond estimates. An example of the geostatistical parameters i.e. grade distribution and variogram is shown in (Figure 6) for a facies of the Venetia pipe. The variogram is an important tool which models the spatial correlation of the chosen variable, in this case grade. The grade data (c/m^3) are positively skewed and the fairly well defined variogram shows a geometric anisotropy.

As stated there are a number of different sample supports (sample masses) at Venetia. Under normal circumstances these data cannot be combined as the sample variance changes with sample support. A mixed support kriging methodology which allows for a kriging algorithm to be applied to samples of differing support sizes has been developed by De Beers in conjunction with Geovariances (the developers of the *Isatis* geostatistical software). As such it requires a support parameter to be defined which separates the various samples into support groups. The technique involves the movement of the sample values to the centre of the blocks that will be estimated. A multi support variance parameter is then calculated, the multi support variance represents the dispersion variance of the sample support in the block and this is calculated by the difference between the dispersion variance of the samples and the dispersion variance of the blocks. The punctual variogram model (Figure 6) that has been chosen (based on the smallest support size) is then regularised to the grid block size and the block variograms are then modelled.

The direct impact of mixed support kriging is twofold; firstly the application allows for any number of different sample sizes to be used simultaneously in the estimation process. Secondly, the algorithm places more emphasis (increases the kriging weights) on the larger support when two or more supports overlap. The concept of mixed support kriging is applied in Venetia type

situations of multiple drilling campaigns but can equally be applied in a production environment where continuous bulk sampling is carried out as part of grade control.

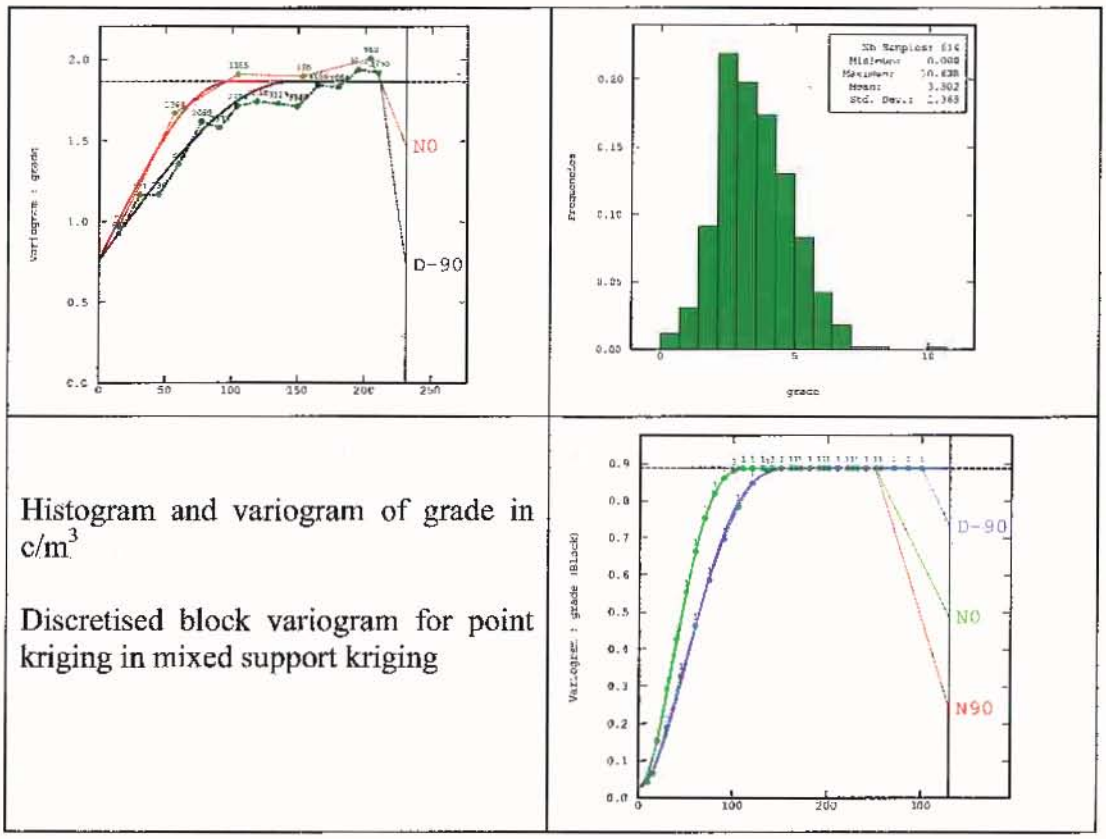

Figure 6 Estimation parameters for a facies at Venetia mine

Another De Beers propriety application in diamond estimation was developed by JJ Ferreira[1] while at the De Beers research centre in Wells, England. This application takes the well accepted micro – macro diamond relationship and places the stone size and stone density distributions on a mathematical basis (Figure 7) by fitting statistical models to the distributions. A micro diamond grade variable is then estimated geostatistically using standard variography and kriging procedures. These models are used to generate local block grade estimates at the requisite bottom cut off.

A further, considerable, deliverable from micro diamond analysis is the size frequency distribution with implications for grade and revenue. This distribution has the potential advantage of a "total content curve" where the effects of comminution are minimised. These curves are important in metallurgical process simulations and may be used as benchmarks in plant efficiency.

[1] Ferreira, JJ. (2009). Sampling for Diamonds in Kimberlite Deposits. Unpubl. PhD Thesis. ENSMP

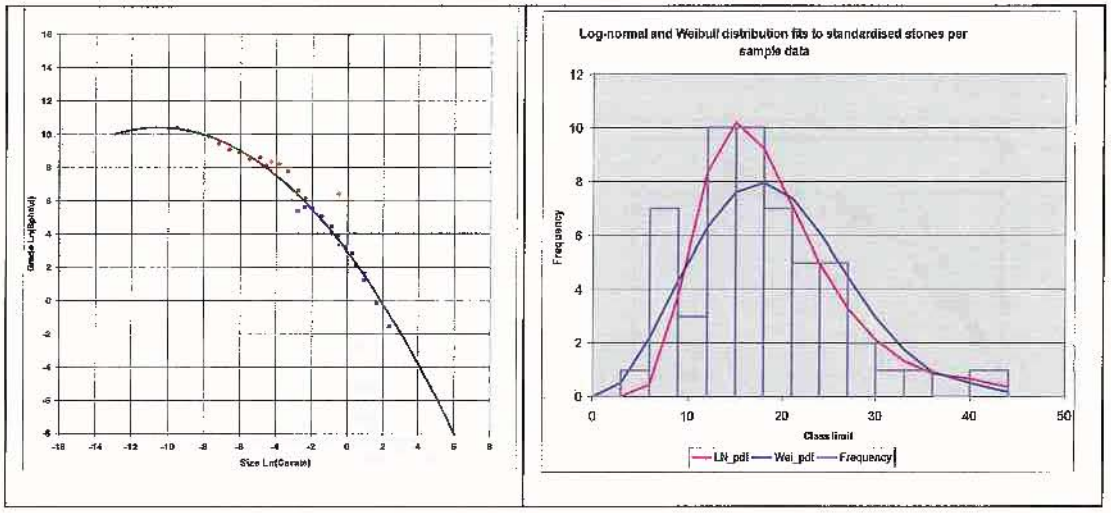

Figure 7 Micro diamond data parameters

The size frequency distribution is the critical link between the grade and revenue variables and as such the resource grade and revenue should translate to an equivalent reserve. This translation involves the top, middle (recrush) and bottom cut offs and their impact on the particle size distributions of the sampling (resource) and production (reserve) comminution circuits. Although not from Venetia, Figure 8 shows the impact on the size frequency distribution and therefore grade and revenue of different bottom and recrush cut off sizes applied to the same resource.

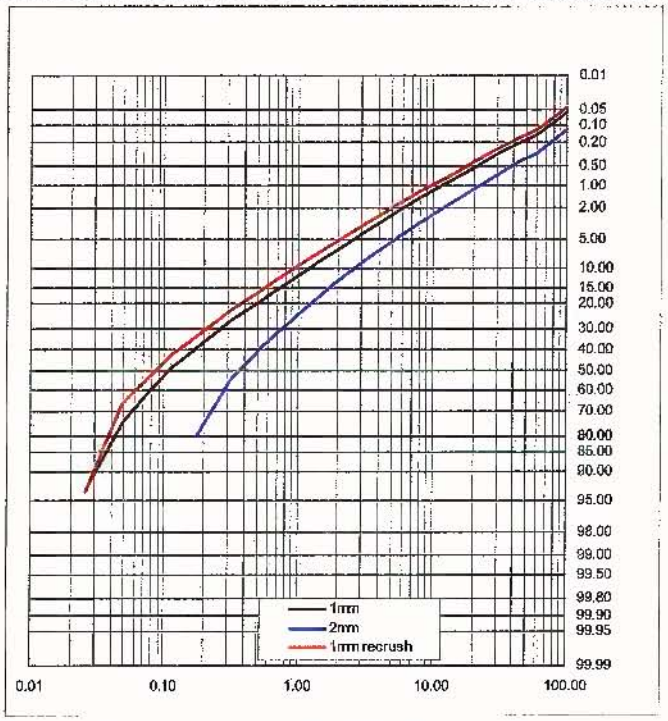

Figure 8 Size frequency distributions and plant cut off sizes

3. Summary

The geostatistical estimation of kimberlite diamond deposits has a number of unique components resulting from the discrete nature of the diamond distribution. Through necessity, a number of De Beer's propriety algorithms and methodologies have been developed that allow for fairly sophisticated estimation processes to be adopted.

Of equal importance however is the "beginning" and "end" of the estimation process. At the outset it is fundamentally important to understand exactly what the sampling data represents; the constraints under which the data were collected (e.g. bottom cut off) and the adjustments necessary to ensure parity between and within sampling programmes. Finally, it is imperative that the estimated resource grade and revenue should be converted to a reserve or production equivalent according to the likely recovery efficiency of the production metallurgical process.

4. Acknowledgements

The author is indebted to De Beers Consolidated Mines and Venetia mine for the use of their data in much of the case study.

To De Beers Group Services (Pty) Ltd for permission to refer to propriety methodologies of grade estimation.

Finally to my colleagues at Z Star mineral Resource Consultants for valuable input in compiling this review.

5. References

Ferreira, JJ. (2009). Sampling for diamonds in kimberlite deposits. Unpubl. PhD Thesis. ENSMP. (in press)

King, HF., McMahon, DW. And Bujtor, GJ. (1982). A guide to the understanding of ore reserve estimation. Aus IMM., no. 281

The Author

David E Bush, *Director*, Z Star Mineral Resource consultants (Pty) Ltd

Joined Anglo American Corp. of SA in 1981 and seconded to De Beers Prospecting in Botswana. In 1984 joined the Ore Evaluation Department (OED) of De Beers in Kimberley and remained in the evaluation field for Anglo American and De Beers until 2007. This period included stints in the diamond revenue section and a secondment to the Free State goldfields.

Along with three colleagues started an independent mineral resource consultancy, Z Star MRC, in 2007