Geostatistical Simulations of Kimberlite Orebodies and Application to Sampling Optimisation

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ABSTRACT

Kimberlite pipes, as opposed to dykes, sill and secondary deposits, are the primary target for diamond exploration companies because they have simple geometries and can contain large volumes of potentially diamond-bearing ore. Once discovered, important decisions have to be made regarding the sampling of these geological entities to establish the total volume of ore present, and to define the internal geology, which can be complex in nature and controls the distribution of diamond grade. It is essential that as part of this process the uncertainty in constructed geological models are assessed. In this paper the Orapa AK1 kimberlite pipe in Botswana is used as a case study to explore a potential methodology for defining this uncertainty.

The uncertainty of the rock volumes of different types can be characterised by a geostatistical approach. Geostatistical simulations, based upon a plausible representation of the geological bodies, provide different possible images of the orebody that can be considered as different realities.

By testing different borehole layouts and drilling the orebody virtually on the computer, many different, but equi-probable realisations of the pipes can be produced. It is then possible to estimate the rocks' volumes and compare them with the actual ones. A statistical analysis of the relationship between estimation error and the number of boreholes can then be used to optimise the next sampling campaign.

The rock volumes are obtained from a two-step simulation process. Firstly, the pipe geometry is simulated by means of introducing variations around the geological block model, by an original method called centre point simulation (CPS), which has been developed for this purpose. Secondly, the internal geology is then simulated within the pipe. The methodology for simulating the internal geological zones has to be adapted to the level of information and to the geological structure itself. The upper portion at Orapa AK1 is filled with sedimentary crater facies. Here plurigaussian simulation techniques can be applied that are adapted to the simulation of sedimentary facies. The central zones of the pipe are typically subvertically-oriented massive volcaniclastic deposits and breccias and the lower regions comprise a complex root zone. CPS is appropriate for these zones.

INTRODUCTION

Kimberlites are ultramafic rocks derived from deep within the earth's mantle. Their deep derivation and their ability to intrude through the thick continental crust means that they are capable of transporting diamonds from the lithospheric mantle to the earth's surface. They are thus one of the primary targets for diamond mining and exploration companies. At the surface these magmas frequently erupt violently to form deep volcanic conduits (commonly 1 - 2 km deep) that are known as 'pipes'. Although they may also occur as dykes and sills, pipes are the primary target for large mines.

Kimberlite pipes have been divided into three zones, or facies, based on their morphological and internal geological characteristics (Hawthorne, 1975; Clement, 1979; Clement, 1982; Mitchell, 1986; Clement and Reid, 1989; Field and Scott Smith, 1999). The uppermost zone is the crater zone, comprised of re-sedimented and pyroclastic kimberlite, which is frequently well layered. The intermediate diatreme-zone comprises mostly massive volcaniclastic deposits, which have been previously termed TKB (for tuffisitic kimberlite breccia), but this is now considered a problematic term (Sparks *et al*, 2006). The lowermost zones are termed the root zone, which is usually a geometrically complicated zone that is made up mostly of hypabyssal kimberlite and breccias. Within each of these zones or facies considerable geological variation can exist, although the level of complexity is usually greatest in the crater and root zones (Clement and Reid, 1989).

Kimberlites frequently weather and alter very readily, and hence they are only very rarely well exposed at the earth's surface. Usually they are found by exploration companies by the use of geophysical techniques and through the sampling for the 'indicator' minerals which, like diamonds, are transported by the kimberlite from the earth's mantle. After discovery of a kimberlite pipe, there is usually very little that can be observed at surface and the outline of the potential orebody is often defined by a geophysical anomaly map. This is often complicated further by the deposition of younger sediments over the kimberlite or by deep weathering profiles. Investigation of the anomaly usually takes place through drilling and geological logging of the resultant cores.

One of the key questions that the exploration geologist has to consider is how many drill holes need to be sunk into the newly discovered pipe to allow a confident decision to be made about the next step that should be taken in the exploration program. In the first instance it is the geology of the pipe that needs to be considered as this should dictate how grade and value sampling should be conducted.

This paper represents an attempt to find a quantitative scientific approach to address this question using geostatistical simulation techniques. The different aspects of the methodology that are applied in this study have already been tested at other kimberlite mines (Deraisme and Farrow, 2003, 2004). In this paper these methods are combined for the first time to produce a single model combining all facies. These techniques are described, and then a case study using the Orapa AK1 kimberlite mine in Botswana is used to demonstrate the technique. Orapa AK1 is very useful because it has a well documented exploration and mining history (Field and Siwawa, 2000). In this paper only the uncertainty in the geological model will be considered, as grade and value sampling are beyond the scope of this investigation.

METHODOLOGICAL FRAMEWORK

Geostatistical background

The ideas that form the basis of the methodology used in this paper can be summarised as follows.

It is assumed that an initial geological model has been constructed and that this geological model is the best available representation of the orebody. In reality it may be considered as only one representation of a spectrum of equi-probable realisations of that model. For example, if the same data were given to three different geologists, three different models could be constructed. It is impractical and time consuming to give it to several geologists, but random variations can be obtained from geostatistical simulations. These differ from Monte Carlo simulations because they take into account the spatial variability of the geometrical parameters defining the geological entities.

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An important consideration that needs to be addressed is how to obtain these geostatistical parameters (variograms) in the absence of real data.

In the case of kimberlite pipes the estimation process attempts to estimate the total pipe volume. Since this is a hard geological boundary it does not require estimating a cut-off grade as is done for many other commodities. As every pipe is unique to some extent, and the pipe boundary is unknown before drilling commences and it is difficult to establish geostatistical parameters for that pipe, ie to establish an experimental semi-variogram. The approach that has been adopted here is that each simulation of the pipe geometry is considered as a reality. This reality is then sampled using a planned drilling layout. The pierce points obtained from such a planned layout are then used to produce an estimate of the volume. The difference between the estimated and the simulated volume represents one outcome of the estimation error. By repeating that process on many simulations, statistics can be created that characterise the distribution of the estimation error.

Simulations of the geometries

The simulation method depends critically on the geometry of the bodies to be simulated. Centre point simulation (or CPS) is used for bodies that have a vertical orientation, such as the whole pipe or diatreme-facies lithologies and plurigaussian simulations (PGS) for the horizontally layered crater facies.

Centre point simulation

The geometry of an ideal kimberlite pipe is a rather simple geometric shape, namely an inverted cone decreasing in volume from top to bottom. This can be readily explained by the current understanding of the formation mechanisms of kimberlite pipes (Field and Scott Smith, 1999; Sparks *et al*, in press). This geometry means that any horizontal slice will produce a shape that tends to be ovoid, which can be described by means of a parametric function where the coordinates of the boundary depends on the azimuth and the radius from a chosen centre point. If the radii were constant, a cone with a circular base would result. By varying the radius with the azimuth and the level, any required shape can be obtained, the only condition being that a one to one relationship exists between radius and azimuth. By digitising the boundary from the input geological model at one degree intervals a mathematical expression for the pipe boundary can be obtained. By superimposing a 3D block model on the outline, each block can be described as being either inside or outside the pipe. The vertical resolution of the block model coincides with the resolution of the geological model, chosen as the height of the mining levels or benches.

As explained in the previous section, the uncertainty in the geometry will be characterised by adding some fluctuation around the geological model. The representation by a parametric function of (azimuth, radius and level) is well suited to that task. The radius is considered as a regionalised variable in the (azimuth, level) bi-dimensional space. As with all regionalised variables, this variable can then be processed by means of geostatistical simulation and kriging. It is appropriate to adopt a non-stationary viewpoint such that the geometry can be guided by the geological model. The radius of the pipe boundary is then decomposed into the sum of the radius from the geological model and a stationary zero-mean residual. Figure 1 shows a comparison between the original block model, one simulation and one estimated model obtained by kriging.

Plurigaussian simulations

Plurigaussian simulations simulate categorical variables, such as (coded) geological facies, by the intermediate simulation of two continuous Gaussian variables. It was developed for simulating lithofacies sequences of oil reservoirs (Armstrong *et al*, 2003).

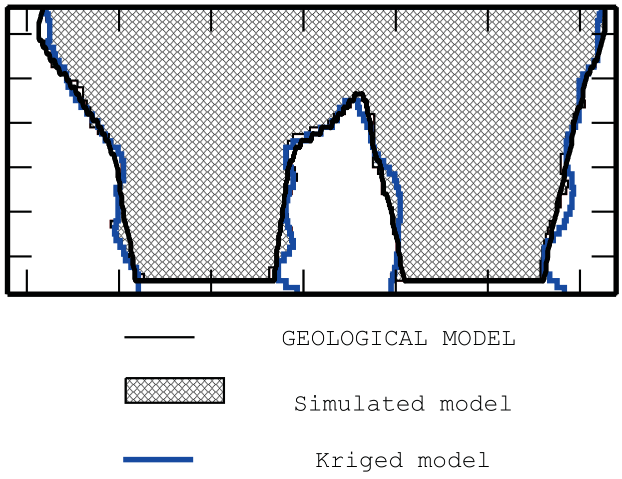


FIG 1 - Vertical NS section of the pipe outlines.

The similarity between the sedimentary sequences hosting oil and crater-facies kimberlites is obvious, although the scale of the deposits is vastly different.

Facies are obtained by applying thresholds to the Gaussian simulated values. The basic idea is to start out by simulating at grid locations one (truncated Gaussian simulation or TGS) or two (PGS) Gaussian variables with a variogram characterising the spatial continuity of the lithotype indicators. Then a 'rock type rule' is used to convert these values into litho-types. It is generally represented by a schematic picture (Figure 2), where the X axis represents the first Gaussian variable and the Y axis the second Gaussian variables thresholds applied vertically and horizontally on both Gaussian variables divide the figure into as many areas as litho-types. That representation of the litho-type rule is useful for defining the authorised transitions between the facies. The conversion from Gaussian variables to litho-types is using the bijection between the Gaussian values and the cumulated distribution function (cdf). Therefore, the application of that method allocates an estimate of the cdf to each grid node. This step is carried out by calculating vertical proportion curves. By interpolating these proportions on the 3D grid, a 3D matrix of proportions is obtained.

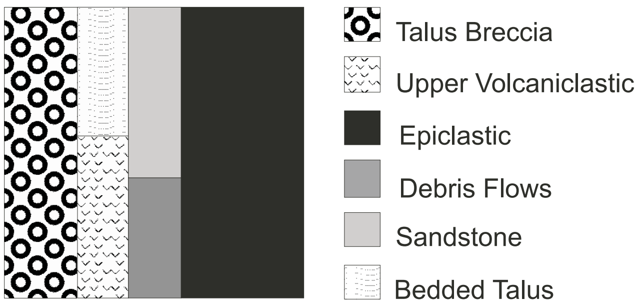


FIG 2 - Litho-type rule for the six facies of the top unit.

The PGS process has four steps:

1. Determination of the vertical proportion curves directly from statistics in the drill hole data. A vertical proportion curve represents the profile along the vertical of the proportions of each facies level by level. These statistics are highly dependent on the choice of a particular surface, the reference surface, which can be interpreted as a guide to the system of deposition of the different lithological facies (commonly an unconformity). The drill hole data will then be transformed into a stratigraphic space where the

reference surface represents the horizontal surface at zero elevation. The simulations of the Gaussian variables will be processed in the flat space before being transferred to real stratigraphic space.

2. Choice of a model describing the relationships between the different facies. This includes the definition of the lithotype rule, the correlation between the two Gaussian variables and their variogram models.
3. Generation of Gaussian values at data locations. This is the most difficult and original part of the method, because at the data locations only facies are known but this does not tell the corresponding Gaussian values. A special statistical method called a Gibbs sampler is used to generate these values.
4. Simulation of the two Gaussian variables followed by truncation to obtain the facies indicators. Finally the simulated facies are transferred to the real space.

Estimation of volumes by planned boreholes

The same methodology has been followed for estimating the volumes of the total pipe and the deeper subvertical internal geological units simulated by CPS. This is to estimate by kriging the radius from the pierce points (intercepts of the planned boreholes with the simulated bodies). Kriging is performed in the polar coordinates system and then it is transferred to real space. But, in contrast to the simulations, here the geological model is ignored for the kriging, making the process similar to a standard practical resource evaluation. An important consequence is that when a small number of boreholes is used, not only is there a high variance of the error, but also a systematic bias occurs because the kriged pipe will look more 'circular' than it is in reality.

For the crater facies the estimation of the volumes is made indirectly, by averaging the error resulting from several PGS simulations conditioned by the same data. These data are obtained by sampling the simulated facies by a set of vertical boreholes located on a regular drilling pattern. It means that nested PGS are carried out:

- A set of simulations conditioned by the actual data is first achieved.
- Each of these simulations is then considered as the reality. Samples from vertical boreholes are extracted from that simulation and used to condition another set of PGS that can be compared to the reality.

ORAPA CASE STUDY

Introduction

Orapa is located 240 km west of Francistown in the western part of the Botswana's Central district (Figure 3). In 2004 it produced approximately 16 million carats of diamonds (http://www.Debswana.com). The mine was discovered in 1967 and has undergone several evaluation programs (Table 1). This well-documented history provides an ideal case study to evaluate how the uncertainty in these parameters varies as more information becomes available.

The geology of Orapa

A review of the Orapa geology is given in Field *et al* (1997) and readers are referred to this paper for a more detailed introduction.

The Orapa pipes intrude into the Archean basement granite-gneiss and tonalities and the sedimentary rocks and lavas of the Karoo Supergroup. The AK1 pipes that make up Orapa Mine are but two of a cluster of over 60 known kimberlites in the area. The deposit comprises two pipes, named the southern and the northern pipes (see Figure 4).

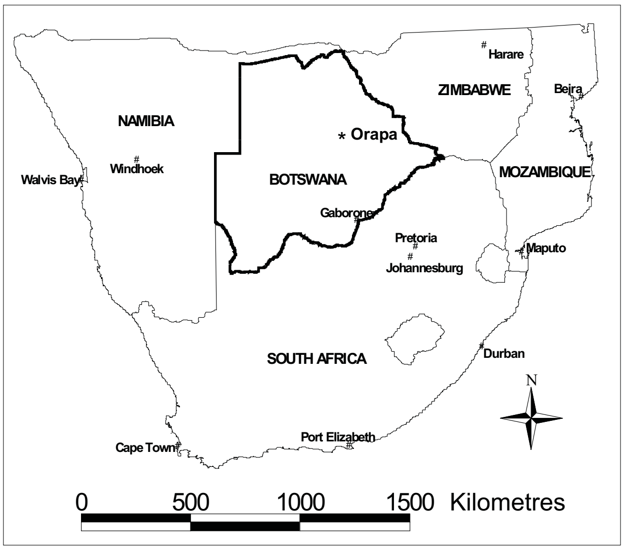


FIG 3 - Location map of Orapa Mine.

TABLE 1

Summary of the evaluation history of Orapa AK1.

Year	Activity	Depth	Grid	Result
1967	Discovery			
1967-68	Pitting	120 ft	250 × 250 ft	
1967-68	Delineation core drilling	100 m	Angled	
1975-80	Pitting	30 m		Proven reserve to 30 m
1982-93	LDD Phase 1	200 m	50 × 50 m	Proven reserve to 200 m
1987-93	LDD Phase 2	250 m	75 × 75 m	Probable reserve to 250 m
1994-97	Deep delineation core drilling	660 m	Angled	Inferred resource to 660 m

The northern pipe was emplaced first and consists of a monotonous sequence of crudely layered volcaniclastic kimberlite (termed NPK). The crude layering is defined by accumulation of basalt and basement-derived clasts. At shallower mining levels this layering was largely subhorizontal in attitude, but it steepens with depth. The layering is on a scale of tens of centimetres to a few metres. It is very discontinuous and can only be traced over tens of metres at most. It was very difficult to correlate layers between drill holes. A further characteristic of the pipe is the presence of numerous vertical gas-escape structures, which are several centimetres wide and up to about 15 m in vertical extent. Petrographically, this rock has features very similar to those described in the diatreme-facies of the archetypical Kimberley pipes by Clement (1982) and Mitchell (1986). From previous drilling programs it was decided to place a subhorizontal subdivision at about 500 m below surface that represents the last obvious layering in this pipe. For the purposes of this exercise it has been decided to ignore this boundary and to assign a single geological code to the whole of the north pipe. It appears these deposits completely filled the northern pipe as there are no 'crater-facies' rocks associated with it.

The southern pipe clearly cuts the north and hence is younger. All of the 'crater facies' deposits at Orapa are associated with it. In contrast to the north, the south pipe has ample evidence for a prolonged depositional history, most notably the presence of three clear unconformities. The first separates epiclastic (termed

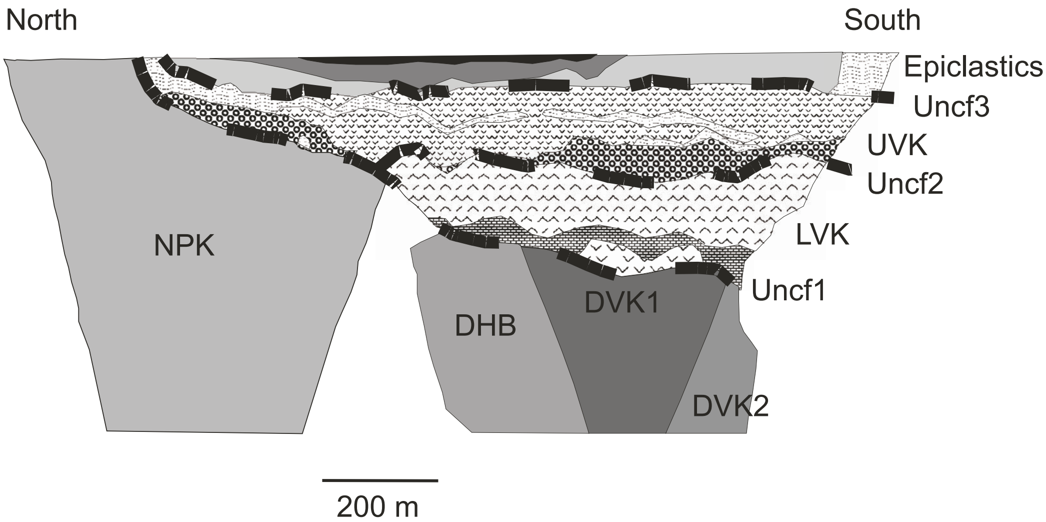


FIG 4 - Vertical north-south section through Orapa AK1 showing the major lithofacies and unconformities. NPK: northern pyroclastic kimberlite; DHB: deep heterolithic breccia; DVK1&2: deep volcaniclastic kimberlite; LVK: lower volcaniclastic kimberlite; UVK: upper volcaniclastic kimberlite; RVK: re-sedimented volcaniclastic kimberlite (or epiclastics). Uncf: unconformity. Ornamentation for the LVK, UVK and RVK are as shown in Figure 2.

RVK) deposits from volcaniclastics. The epiclastic deposits are those in which sedimentary processes can be identified and comprise a wide variety of types including talus deposits (well sorted grain flows and poorly sorted breccias), debris flow breccias, boulder beds, grits and lacustrine shales. These deposits are generally oxidised and in the case of the lacustrine beds contain fossils. They are also laterally continuous. Below the first unconformity are sequences of green coloured volcaniclastic deposits, which have no obvious mechanism of deposition. They are highly variable in character, with well sorted bedded horizons but dominated by coarse massive, matrix supported types. No convincing directional sedimentary structures have been found within these deposits. The second unconformity separates these from further volcaniclastic deposits, which contain beds of definite pyroclastic origin, including pyroclastic flows and falls. At the base of these deposits are basal heterolithic breccias, which apparently mark the base of the crater zone. These breccias occur intermixed with the volcaniclastic deposits.

The base of crater breccias marks the third unconformity. Below these breccias there is a sharp transition into dark, dense volcaniclastic kimberlite, which is very similar to the diatreme-facies kimberlites that occur at nearby Letlhakane Mine. On petrographic grounds this kimberlite has been divided into two varieties (SDVK1 and SDVK2). These rocks persist as far as exploration has been carried out so far, ie to 660 m below surface.

A further feature of the deeper deposits is the existence of a broad heterolithic breccia (termed DHB) envelope around the northern and western side of the south pipe. These breccias contain clasts that are derived from local country-rock lithologies. There has been a slight downward displacement of these clasts relative to their original positions in the wall rock sequence.

For the purpose of this study the internal geological subdivision of the Orapa kimberlite has been simplified as shown in Figure 4. The second and third unconformities feature strongly in the plurigaussian simulation below.

Scenarios for the simulations

The primary input for the simulations is an initial geological block model, with a value assigned to each block of fixed dimension (here 5 m × 5 m × 15 m). The value may be either a code that indicates if the block falls either inside (value of one) or outside (value of 0) the pipe, or it is a geological facies code.

Three block models have been constructed for this exercise, and these have been named BM1, BM2 and BM3. BM1 was constructed as being equivalent to what might be expected immediately after discovery. Here only a surface outline is known (in the case of Orapa this could be obtained from an aerial photograph, but in other situations it could be a geophysical outline). In this case previous experience is used to predict what the total volume of the pipes might be. In the case of BM1 a downward projection of 82 degrees is used. This value is taken from Hawthorne (1975) who showed that this is a reasonable average inward dip for kimberlite pipes.

As more information becomes available (geophysics and early drilling) a better estimation of the total volume can be obtained form additional drilling and geophysical surveys. BM2 is such an improvement.

BM3 is the currently accepted model for Orapa and is based on a considerable amount of drilling and in-pit mapping. This model is the only one that contains a geological interpretation of the internal facies as well as actual vertical boreholes with crater facies data.

The simulations are carried out in three main steps:

1. Simulation by the CPS method of the pipe boundaries. It is achieved by simulating two pipes (northern and southern pipes) that are merged together.
2. Simulation of four diatreme facies below the crater basis by the CPS method.
3. Simulation of the crater facies by the PGS method applied independently on two units separated by the Lower Volcaniclastic unconformity: six facies are simulated on top of that surface and three facies are simulated below that unconformity and the crater basis. The volumes limited by these surfaces are visualised on the Figure 5.

At Orapa, the actual kimberlite-wall rock contact has not been well exposed to date, and thus deviation between BM3 and reality cannot be adequately assessed at this time. A pure heuristic approach may be the only solution, with the condition that the simulated geometries look acceptable when compared with the initial geological interpretation.

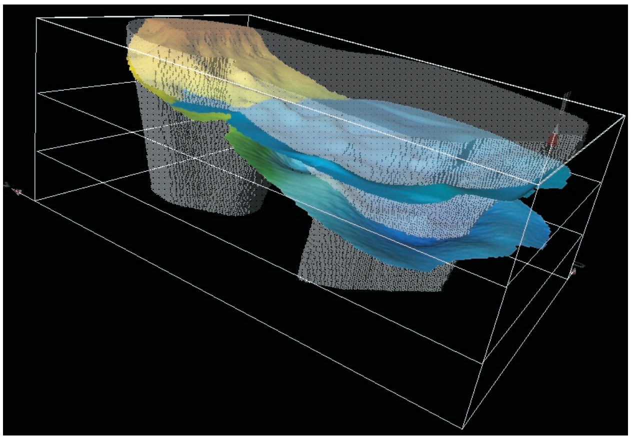


FIG 5 - Reference surfaces for PGS of top and bottom units (Isatis 3D viewer).

Nevertheless some real data from the much smaller Lethlakane DK1 pipe, 40 km south-east of Orapa, where the actual pipe boundary has been exposed over 15 benches, have been used to calculate the horizontal variogram of the difference between the actual pipe boundary and an original model (Figure 6). This at least provides some indication of the order of magnitude by which the range (distance of correlation) and sill (variability) parameters of the simulation can be varied. The other advantage of considering this data is that this pipe cuts through the same country rock sequence as AK1.

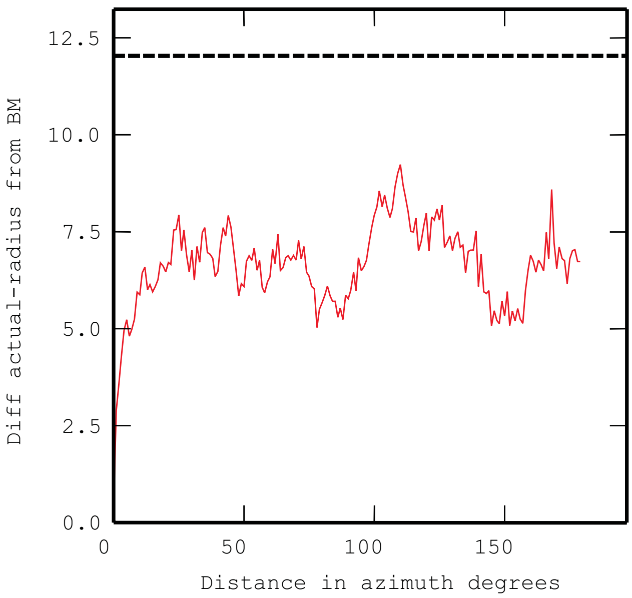


FIG 6 - Variogram of the residual radius, difference between actual observed outlines and those predicted by an initial geological model (the distance is expressed in degrees and is calculated in polar coordinates).

The role played by the initial geological model is critical. In the example presented in the Figure 7, it is clear that increasing geological knowledge can transform the pipe geometry considerably: for instance initially a single body is detected, which is then split into two pipes. The three geological models are not only very different from the point of view of their shape but they also contain significantly different kimberlite volumes. In this case a substantial decrease is observed as more information is obtained.

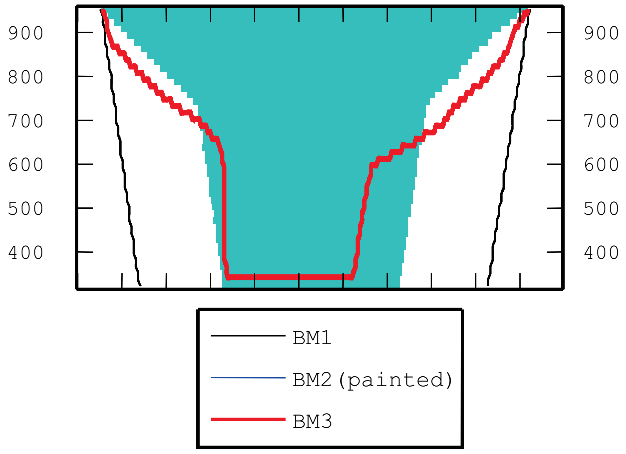


FIG 7 - Vertical west-east view showing the envelope of the three pipe geometries (BM for block model).

In an attempt to optimise the sampling strategy, the process has been designed to take a basic borehole layout and then choose subsets of these boreholes. These subsets are chosen by taking randomly a given proportion of the whole set of boreholes, specifically 20 per cent, 40 per cent, 60 per cent and 80 per cent. For each subset, estimation errors are calculated and therefore the errors associated with different numbers of boreholes can be compared.

For this study the following suites of planned drill hole layouts have been tested:

1. Grids of vertical holes with spacing of 200 × 200 m, 100 × 100 m, 50 × 50 m.
2. Angled fans of holes located near the centres of the two pipes. At each centre a vertical hole and pairs of angled holes drilled at 45 and 60 degrees have been planned. The azimuth of the angled holes is varied in sets of 15, 30, 45, 60 and 90 degrees.
3. Holes designed to outline specific horizontal levels, with pierce points approximately every 50 m along each level. The vertical distance between levels is varied in steps of 45 m, 60 m, 75 m and 90 m. In each case the upper most level (ie outcrop) is taken as fully defined and geostatistical parameters used for the simulations and estimations are kept constant.

At Orapa the crater facies have been simulated in two sedimentary units: the top unit is delimited by the top surface and an intermediate surface (upper LVK surface, or second unconformity in the geology section above), which contains six facies and the bottom unit delimited by the upper LVK surface and the base of the crater surface, or the third unconformity.

RESULTS

Pipe simulations

The results are obtained from 50 CPS simulations and 50 PGS simulations.

Three points are of particular interest:

- the variability of volumes with the geological model and how it can be reduced when adding actual data;
- the sensitivity of the volumes' variability to statistical parameters; and
- the relationship between the general boreholes layout, the number of boreholes and the estimation error (mean and variance).

Variability of volumes with the input data

The most important factor for the total pipe volume is the initial geological model, since the simulations do not change the general shape. By adding actual pierce points (the rank of the block model is then four) that are used to condition the simulation, all simulations are more similar and then the volume variability decreases (Figure 8).

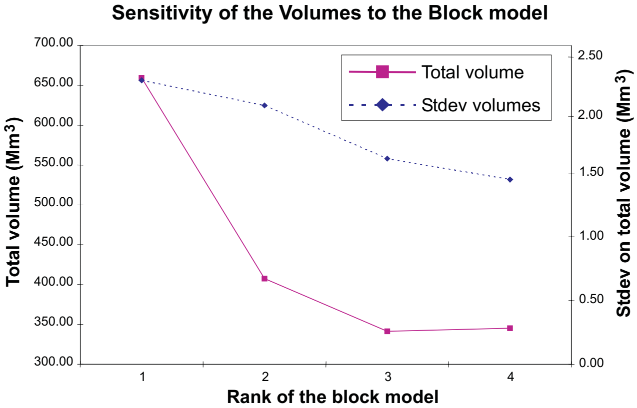


FIG 8 - Variation of the pipe volume with the geological model.

A comparison between non-conditional simulations and the actual pierce points (Figure 9) may lead to an update of the geological model when the difference exceeds a given threshold.

The majority of the boreholes are in agreement with these statistics, since 95 per cent of the holes are within ±30 m of the pipe contact. This is twice the standard deviation of 15 m, the square root of the variogram sill.

Sensitivity of the volumes variability to statistical parameters

Sensitivity studies have been conducted for the CPS simulations. The statistical parameters that were varied are the horizontal and vertical ranges and the sill of the variogram of the residual between the initial block model and the simulated model. This is applied to both the total pipe and internal geology cases. In the polar coordinate system the horizontal range is the range in azimuth degrees. For example a range of 60 degrees means that for two points making an angle of more than 60 degrees their radii are not correlated. The following values have been tested:

- azimuth range: 15°, 30°, 60°, 75°;
- vertical range: 80 m, 120 m, 200 m; and
- sill of 20, 40, 100, 250, 10 000.

In Figures 10, 11 and 12 the results of the sensitivity studies (as applied to BM1) are displayed.

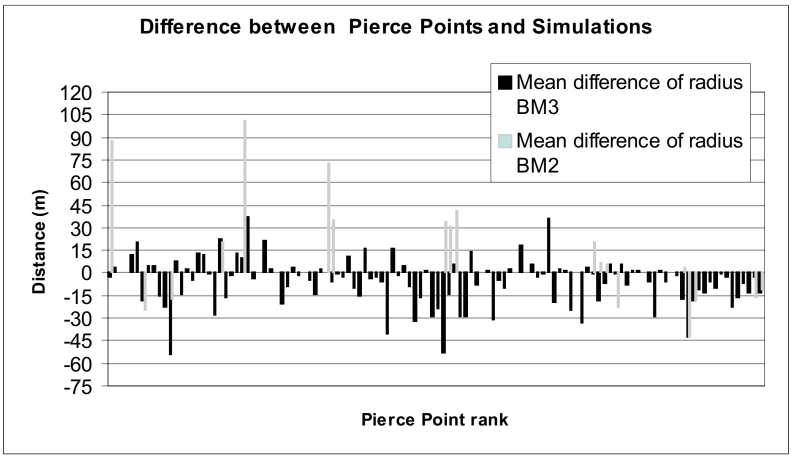


FIG 9 - Average of the difference in metres between the actual pierce points and non-conditional simulations ignoring these data with a sill of 250 m^2.

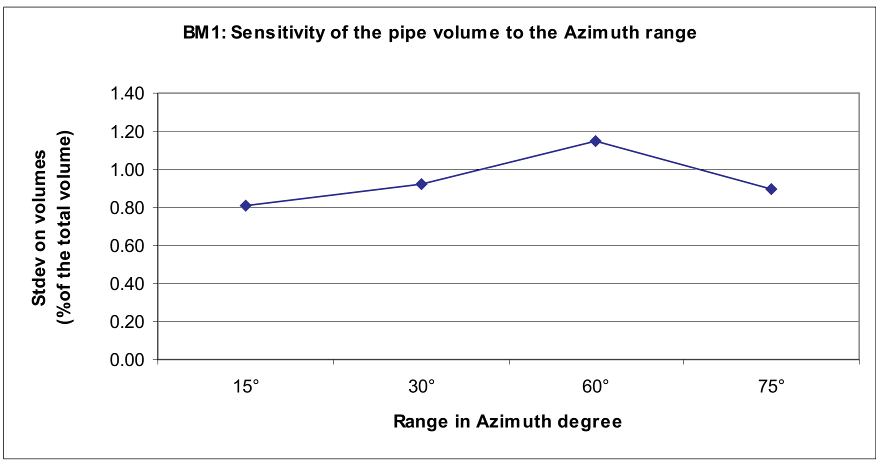


FIG 10 - Sensitivity of the total pipe volume to the horizontal range.

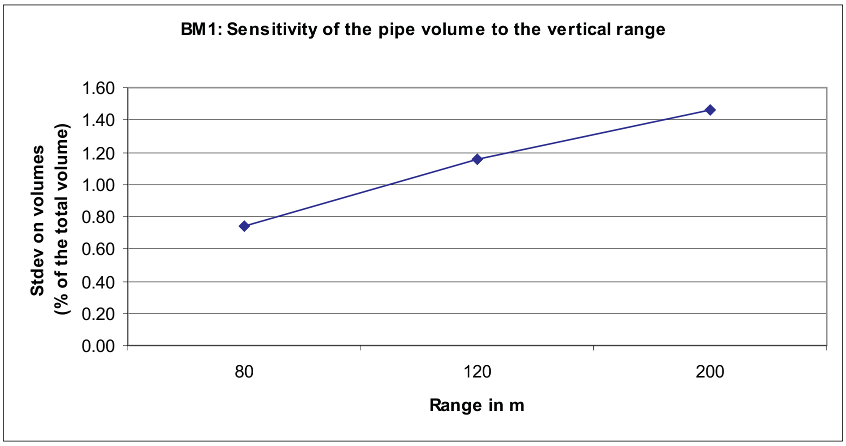


FIG 11 - Sensitivity of the total pipe volume to the vertical range.

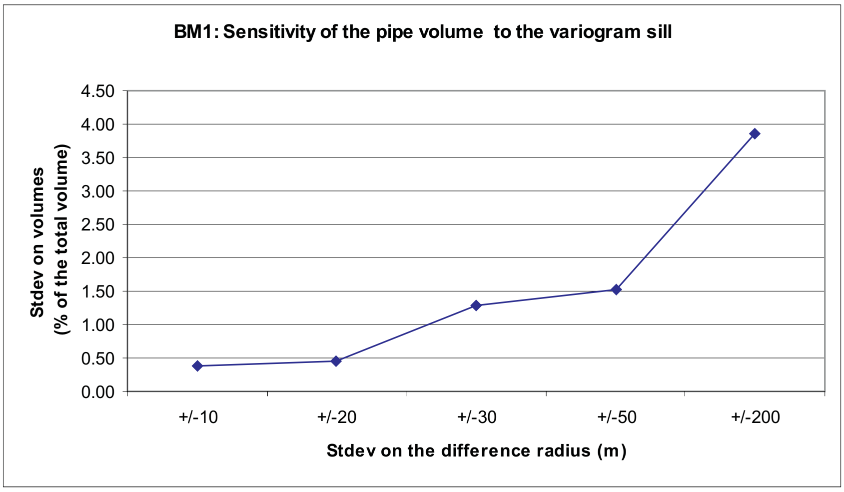


FIG 12 - Sensitivity of the volume variability to the variogram sill.

The increasing variability of the pipe volume with increasing azimuth and vertical range of the variogram of the residuals (Figures 10 and 11) meets the expectation. Intuitively, the higher the range the greater the chance of generating geometry that significantly departs from the initial geological block model, and hence a greater variability between the simulated volumes. The periodic nature of the horizontal range may explain why after a peak of 60° in the azimuth range the variability decreases again. The influence of the range parameters on the volume variability is low (<1.2 per cent).

When the variogram sill is considered (Figure 12) it is evident that the variability of the total pipe volume is low (<4 per cent). This is so even for a very large sill value (such as 10 000). This is an important point since the simulated geometries are all influenced by the initial geological block model. It should also be kept in mind that the simulations, as many they are, do not replace the acquisition of real data for assessing the input parameters of those simulations.

In the absence of quantitative data, a heuristic approach has been adopted by studying the outputs of the parameter testing procedures. Based on this approach the following parameters were chosen because they produced the most geologically reasonable results:

- azimuth range = 60°,
- vertical range = 120 m, and
- sill = 250.

Relationship between the number of holes and the error statistics on the pipe volumes estimated using different borehole layouts

Two statistics have to be considered: the average error that evaluates the possible bias (MBE for mean biased error) and either the standard deviation of the error or the mean absolute error (MAE).

The errors on the total volume (pipe and internal geology) as well as the error on the volume level per level have to be considered. Attention is paid to the shape of the curves in order to determine the optimal value of the number of holes.

It is rather obvious that the boreholes layout is as important as the number of holes. For the crater facies only vertical boreholes with different spacing have been considered, as it is essential to capture the vertical variability.

For the diatreme facies the degree of freedom is higher. To understand some intuitive key parameters different patterns of boreholes have been designed as described above.

Applying the methodology described above, results for the total pipe volume were obtained for 50 simulations for each of the sampling patterns. The results for MBE are summarised in Figure 13 (the error is calculated as the difference between the simulated and the estimated pipe volume).

The pipe volumes are systematically over-estimated when boreholes are too sparsely located, except when the boreholes are

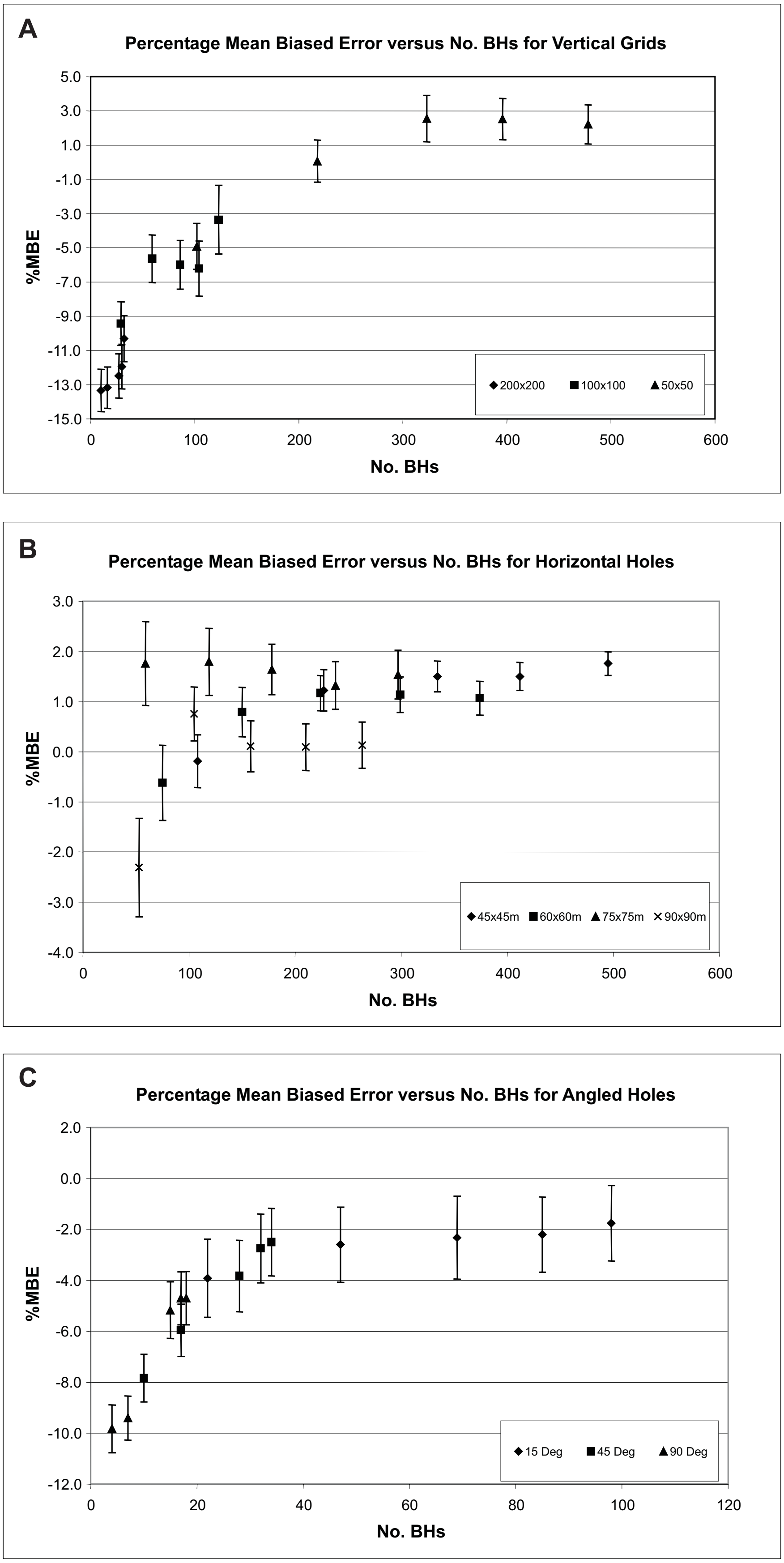


FIG 13 - (**A**) Results of 50 simulations and estimations performed using grids of vertical holes spaced 200, 100 and 50 m apart. (**B**) Estimation error for the total pipe using horizontal drill holes. (**C**) Estimation error for the total pipe using angled drill holes. The error bars represent one standard deviation of the mean biased error.

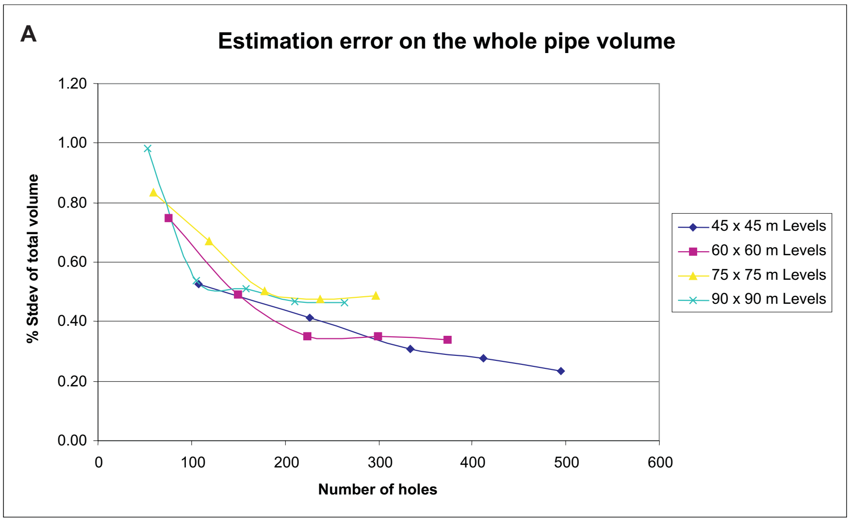
drilled horizontally. In the procedure the uppermost level of the pipe is considered as known and this boundary is added to the actual pierce point's database at the simulation stage as well as to the pierce points from the planned boreholes at the kriging stage. The overestimation of the volumes can be explained by the fact that with inclined or vertical boreholes the probability to obtaining pierce points close to the surface is low, and the top surface, which has the largest volume, is then extrapolated to the first levels.

With horizontal boreholes the mean biased error is very low even if the number of boreholes retained is relatively low. It is then important to consider the dispersion of the error (Figure 14a). With the possible exception of the boreholes spaced every 45 m, it appears that the decrease is not linear. After about 170 boreholes the improvement in the estimation error is relatively small compared to what was obtained for the first 100 holes. Nevertheless the overall variance of the error is quite low (ie less than one per cent) when compared to the total pipe volume. This is not surprising because for a large volume most of the errors are compensated. It is important to consider the estimation error for smaller volumes. In Figure 14b the standard deviation of the estimation error for the level-per-level volume is displayed. The inflection in curves of decreasing standard deviation is also evident in this data. By relating the pipe volume of one level to a given rate of production, these graphs could be used in the definition of resource classification.

Internal geology simulations

The simulations of diatreme and crater facies were examined to assess whether they are geologically plausible. It is clear from Figure 15 that this objective has been achieved. The same statistics have been calculated for the lower internal geology simulated by CPS. Because the facies are oriented vertically it appears that only horizontal borehole layouts can provide a sufficient number of pierce points.

For the crater facies the method used for estimating the volumes is more complex since it is based on nested simulations by PGS. The first set of simulations is considered as equi-probable outcomes of the actual facies; they are conditioned by the actual boreholes. The second set of simulations is based on sampling by planned boreholes of each initial simulation; the actual boreholes are then ignored. In the case of Orapa more than 600 boreholes have been used to calculate the vertical proportion curves but the number of actual boreholes used for conditioning the first simulations is less (90), because only these are considered as reliable at the local scale. Nevertheless a large number of data has been used for generating the simulations. It has led to a limited number of simulations been run in order to characterise the relationship between the number of boreholes and the estimation error, namely five simulations for the first set and ten simulations for the second set, making 50 simulations of the estimation error. Figure 16 illustrates how that relationship has been quantified.



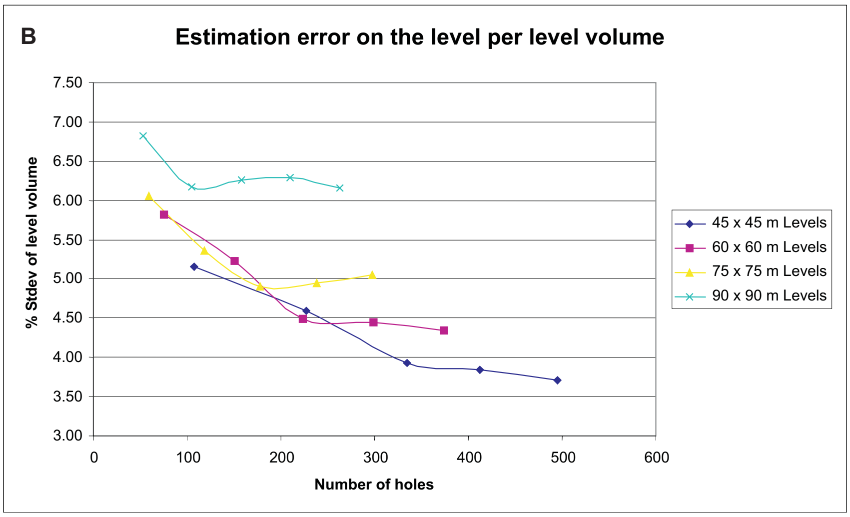


FIG 14 - Standard deviation of the estimation error of (**A**) the whole pipe and (**B**) the level per level volume as a function of the number of boreholes.

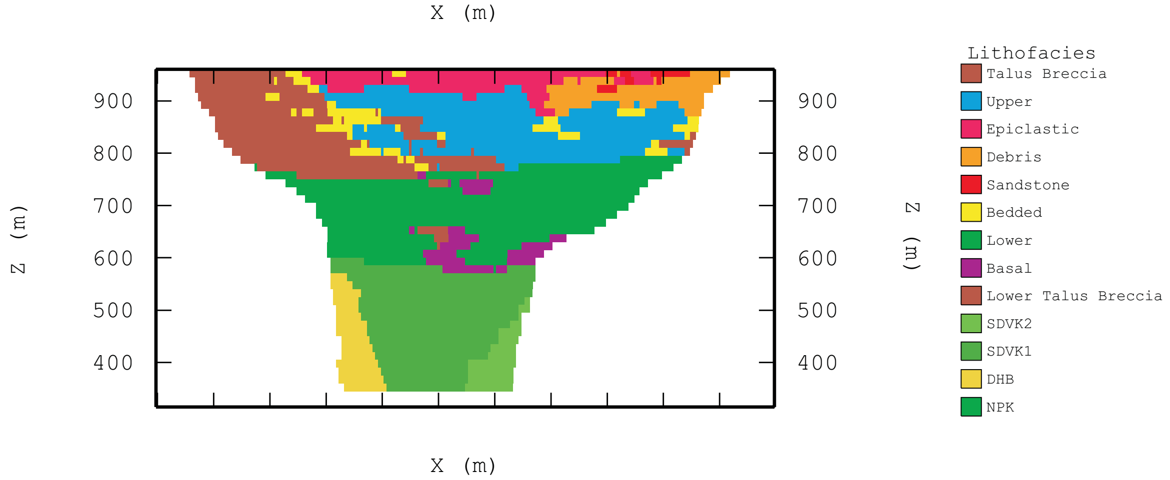


FIG 15 - Vertical west-east section of the combined simulated pipe and internal geology for the entire orebody.

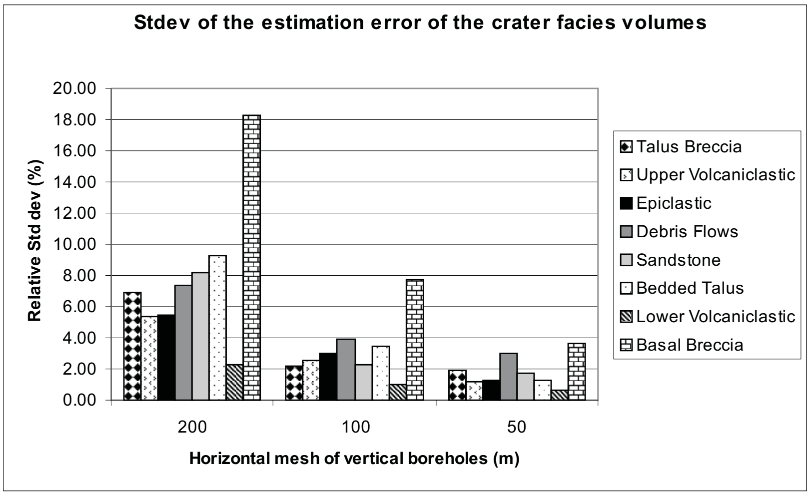


FIG 16 - Standard deviation of the estimation error of the crater facies volumes as a function of the boreholes mesh.

CONCLUSIONS

Simulations of the kimberlite pipe and internal geology reproduce satisfactorily the main features of the geology. The methodology makes the use of the best existing information to assess the uncertainty associated with different sampling patterns. The results will provide a useful guide in sampling the pipes and will assist economic decision making.

It is intuitive that horizontal sampling for vertically oriented structures is optimal, while vertical boreholes are appropriate for subhorizontal structures. The added value of such a simulation approach is to optimise the characteristics of the sampling (vertical spacing in the first case or grid mesh in the second case) in relationship with the pipe's structural features. In case of Orapa AK1 these characteristics are vertical intervals of 60 to 75 m and horizontal grid mesh less than 100 m.

Some of the parameters used, particularly those related to the variograms, are not simple to choose and this problem will be particularly difficult for new discoveries. It is important that sensitivity studies are conducted to assess the geological appropriateness of the chosen parameters.

From the simulations of the geometrical characteristics of the kimberlite some mean or extreme (optimistic or pessimistic) scenarios can be extracted in order to populate the models that form the framework for other key parameters such as density and grade.

This project has been entirely achieved by using the Isatis™ geostatistical software. The whole procedure can run in batch mode and can be customised to other pipes.

ACKNOWLEDGEMENTS

The authors would like to thank De Beers MRM R&D for permission to publish and for funding the work. We would also like to thank Grant Nicholas (De Beers MRM), for his contribution to the discussions on the concepts and Jerome Poisson (Geovariances) for his involvement at various stages of the project and review of the paper.

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