GEOSTATISTICAL SIMULATION TECHNIQUES APPLIED TO KIMBERLITE OREBODIES AND RISK ASSESSMENT OF SAMPLING STRATEGIES

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Abstract. Typically a kimberlite diatreme has several different geological zones. The upper portion is generally filled with the sedimentary crater facies, the central zone is more typically an in situ massive series of volcanic breccias and the lower regions comprise a complex root zone. Depending on the local degree of erosion, not all zones remain at any particular kimberlite occurrence.

A method of simulating the simpler internal geologies seen in the central region had previously been developed using a geometrical technique. In the upper reaches of the diatreme zone, the geologies have more complicated geometries and the approach adopted for the central regions needs to incorporate a more sophisticated method of simulating the internal geologies.

The similarity between the sedimentary facies that comprise the crater zone infill and the sequences that the oil industry targets as oil reservoirs suggest a similar technique could be applied to the simulation of internal geology of crater zone of kimberlite pipes.

Previous work has shown that a truncated gaussian approach can be useful, but the restrictions on facies relationships have limited its implementation. Plurigaussian simulation allows more complex interrelationships to exist between the simulated zones.

In conjunction with other geometric simulations, plurigaussian simulation can be used to guide sampling programs to optimise sampling layouts and sample size and ensure that the goals of the sampling programs are attainable. This paper focuses on the application of the combination of these simulation techniques and will be illustrated by a case study.

1 Introduction

The Orapa Kimberlite Mine forms the basis for this study. The mine, located 240 km west of Francistown in the western portion of Botswana Central district, (Figure 1) produces approximately 6 MCts per year with a value of almost US$ 500 million.

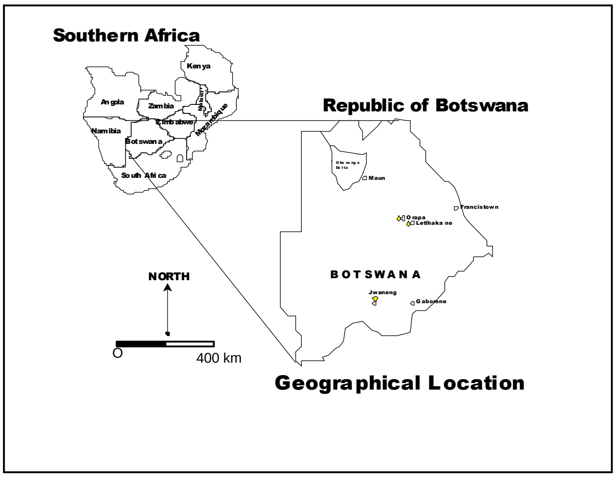

Figure 1 Locality Map of Orapa

Typically kimberlite pipes have a number of differing zones or facies. Three facies, namely “crater”, “diatreme” and “hypabyssal” have been recognised in the Orapa orebody. The Orapa orebody comprises two volcanic pipes, which coalesce to form the single crater. The focus of this study is the crater facies rocks of the upper portion of the southern pipe.

The crater facies comprise a predominantly sedimentary type sequence of volcanic materials that have been re-deposited into the volcanic crater. Application of the Plurigaussian Simulation technique to the crater facies has been investigated for assisting with the creation of geological block models and determining an optimal sampling configuration.

Numerous boreholes and pit exposures have been combined into the digital geological model using GEMCOM™ software for analysis and visualisation, typically a time consuming process. During mining, and as additional drilling is undertaken, more data becomes available. Incorporating additional data into the digital model requires that the models be regenerated, recreating the digital model to ensure that the spatial distributions are maintained, once again a time consuming process. As a consequence, the digital models are not updated with any regularity and the mining models and the geological models frequently differ. This results in sub optimal Resource Management. An algorithmic method of more rapidly generating an overall geological model which can be updated on a regular basis is required.

Initial investigations were undertaken using the truncated gaussian approach. Despite showing promise, it did not prove very effective. The plurigaussian simulation methodology implemented in the latest release of the geostatistical software, ISATIS™, offers enhanced capabilities for geological modelling. This has been successfully applied to the geological simulation of oil reservoirs.

2 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. For the purposes of this study only the major rock types of the crater facies are summarised.

The Orapa pipes intrude into the Archean basement granite-gneiss and tonalities and the sedimentary rocks and lavas of the Karoo Supergroup. They were covered by extensive thicknesses of Cenozoic and Mesozoic deposits. The deposit comprises two pipes, named the southern and the northern lobes. Rocks belonging to the crater, diatreme and hypabyssal facies, as described by Hawthorne (1975), have been recognised.

The Crater Facies deposits are well preserved and divisible into epiclastic, volcanoclastic and pyroclastic varieties. The epiclastic deposits are those in which the sedimentary processes can be identified and comprise a wide variety of deposits including talus deposits, debris flow material, boulder beds, grits and lacustrine shales. Those deposits with no obvious mechanism of deposition are termed volcaniclastic. They are highly variable in character, with well sorted bedded horizons but dominated by coarse massive, matrix supported deposits. No convincing directional sedimentary structures have been found within the deposit. Basal Hetrolithic Breccias which apparently mark the base of the crater zone deposits, occur intermixed with the volcaniclastic deposits. Pyroclastic deposits show evidence of direct deposition from volcanic mechanisms. The Pyroclastic deposits are present only in the northern pipe and comprise materials that exhibit evidence of pyroclastic fall, flow or surge.

3 The Plurigaussian Simulation Methodology

Plurigaussian simulation (PGS) aims to simulate categorical variables, such as geological facies, by the intermediate simulation of continuous Gaussian variables. The facies are obtained by applying thresholds to the Gaussian simulated values. A detailed review is given in Armstrong et al. (2003). PGS is an extension of Truncated Gaussian simulation (TGS) which implies a rather strict stratigraphic sequence. The fundamental concept of non stationary proportion curves is central in TGS, where the so-called rock type rule plays an essential role in producing realistic models that represent the transitions between the different facies. The key point is that the Gaussian variables and the indicators are linked by means of the thresholds but, even if the indicators are not stationary, they can be obtained by truncation of stationary Gaussian variables. Initial applications were made in the petroleum industry where this approach seems natural due to the sedimentary origin of the reservoirs. The analogies with orebodies where mineralization occurs in layers forming a consistent stratigraphy justifies the application of the same conceptual model.

The process has three steps:

- determination of the vertical proportion curves from statistics on the drill-hole data. 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. The drillhole data will then be transformed into a “flattened” space where the reference surface represents the horizontal surface at zero elevation. The simulations will be processes in the flat space before being transferred to the real stratigraphic space.

- 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.
- simulation of the two Gaussian variables followed by truncation to obtain the facies indicators. Finally the simulated facies are transferred to the structural grid.

4 Data Sources

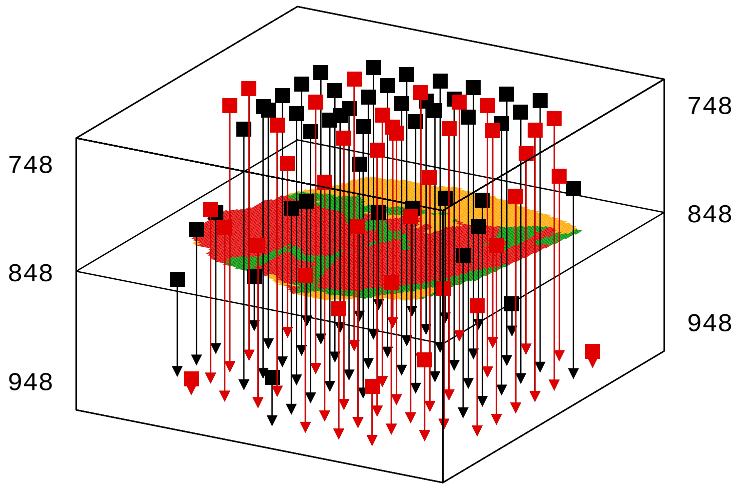

Figure 2**:** Vertical boreholes spaced on a 100m square grid, sub-sampled 200m grid boreholes in red.

The most recent geological model was transferred to a 5m * 5m * 5m block model. This was taken as the starting point of the work. Simulated boreholes were generated from the geological block model on 100 m, 150m and 200 m square grids. The facies observed on the simulated boreholes from the geological model are considered as the “reality” and are used to condition the facies simulations. The aim is to determine how much drilling is required to produce an accurate model of the pipe geology and associated volumes.

5 The Simulation

5.1 CHOICE OF A REFERENCE SURFACE

This is a crucial decision that has consequences on all stages of the process, data analysis and simulated images. In a sedimentary context the reference surface is meant to represent the direction perpendicular to the deposition of the different facies. When comparing facies parallel to that surface, more similarity is expected and consequently more correlation between boreholes than along parallel plane surfaces will be observed. The consequence on the simulated images will be to force the facies to be stacked in parallel to the reference surface. In the present case, a bowl shaped surface showing the angle of dip of the bedded horizons in accordance with the proximity to the pipe boundaries was used.

5.2 VERTICAL PROPORTION CURVES

The boreholes have been discretized by cores of 5m in length and repositioned relative to the reference surface. For each case corresponding to the different horizontal spacing the vertical proportion curves have been calculated and averaged within polygons designed in order to take account of the lateral facies change (Figure 3).

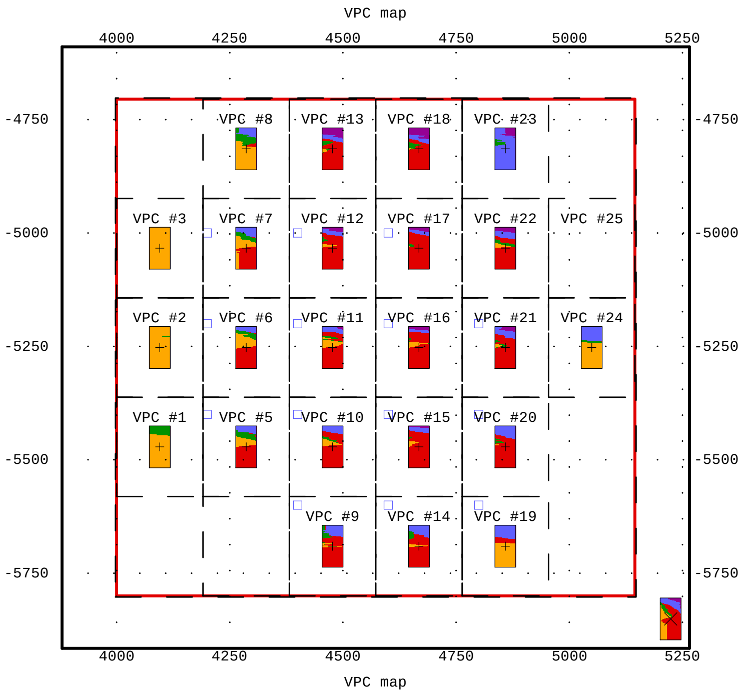

Figure 3: Vertical proportion curves calculated from boreholes within 2D polygons.

5.3 3D PROPORTIONS

The vertical proportion curves have then been interpolated on each grid cell by a kriging procedure with a rather long range (2 km) variogram, making the change of the lithotype proportions gradual. This gives a 3D matrix of proportions that will be used to calculate local thresholds on the Gaussian random functions (Figure 4).

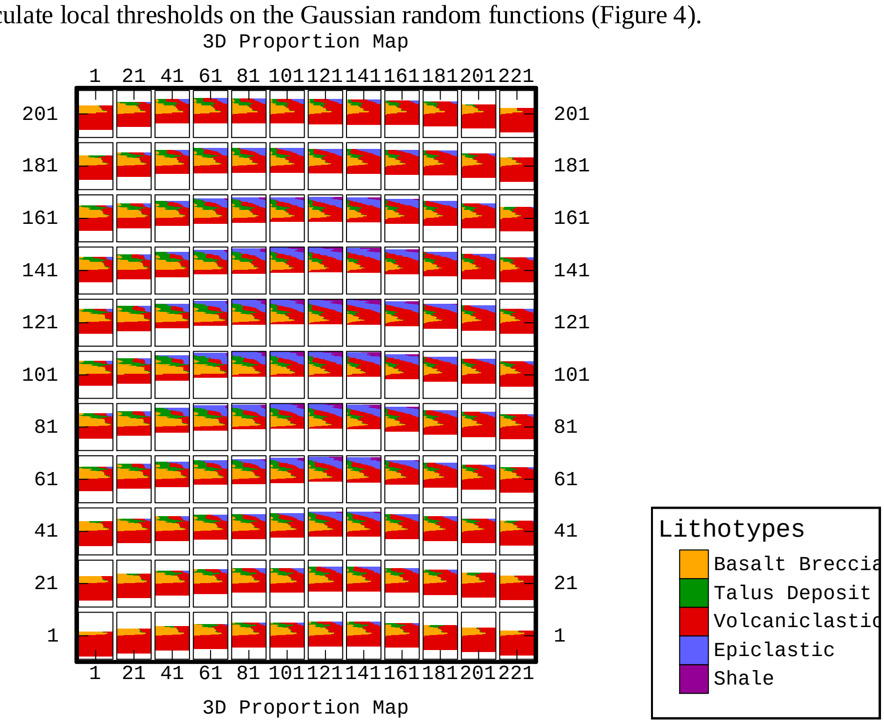

Figure 4: 2D representation of the 3D proportions interpolated on the grid in the flat space.

5.4 LITHOTYPE RULE

The knowledge of the lithotype proportions is not sufficient to derive the values of the thresholds to be applied on the simulated Gaussian values. Additional information on a partition of the 2D gaussian space is required. Depending on the number of facies, there is a finite number of rectangular partitions that may represent the relationships between the Gaussian random functions and the lithotypes. From these we chose the most sensible from a geological point of view, considering the probable transitions between the facies. For instance, since the shale occurs on the top of the diatreme adjacent to the epiclastic deposit, while the basalt breccia mark the base of the crater, it is appropriate to differentiate the corresponding lithotypes on the first Gaussian function. The representation (Figure 5) is schematic: the thresholds will be calculated at the simulation stage. In this example the lithotype rule implies that Basalt, Epiclastic and Shale are dependent only on thresholds applied on the first Gaussian function, while the Talus and Volcaniclastic also depend on the second Gaussian function.

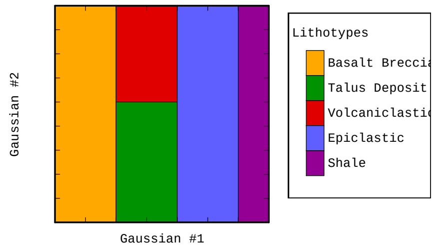

Figure 5: Rectangle lithotype rule.

Once the lithotype rule is defined, the variograms of the Gaussian functions can be modelled. The prevailing role played by the proportion curves does not mean that the choice of the variogram has no consequence. This is illustrated in the Figure 6, where the range of the variogram used for the first Gaussian functions has been reduced. In the lower picture the 3 lithotypes (orange,blue and purple), that are only discriminated by the first Gaussian function look much less continuous than on the upper picture. The second Gaussian function was simulated in correlation with the first (coefficient of correlation of 0.7) in order to make the Talus facies (green) preferentially conformable to the Breccia facies (orange).

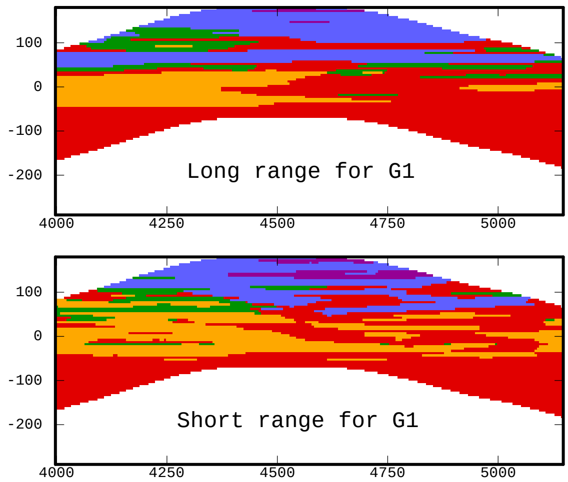

Figure 6: Cross section (in the flat space system) of two simulations changing the horizontal range of the variogram associated to the first Gaussian function.

CONDITIONAL SIMULATIONS

The simulations, achieved by means of the turning bands method, are performed in flat space, then transferred to the real “stratigraphic” space. Figure 7 compares the original geological model to 3 different realizations obtained from plurigaussian simulations using either no boreholes (just the average proportions) or boreholes (BH) spaced every 200m or every 100m. It is observed that with an increasing availability of data, the simulations converge towards the supposed reality.

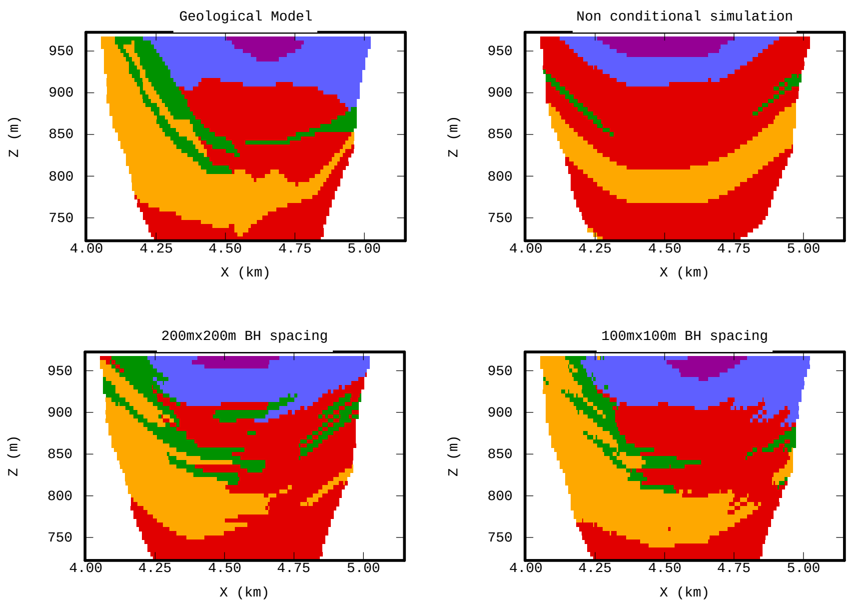

Figure 7: Cross section of three plurigaussian simulations with increasing information rates compared to the original block model.

6 Results

In the scope of evaluating the level of uncertainty in the volume of each lithotype, statistics have been calculated on the difference between the original block model and the simulations based on different levels of information. By comparing different borehole spacings (100m, 150m and 200m) it appears that 150m provides a satisfactory global estimation of the different facies (Figure 8 where the density of boreholes has been transformed into metres drilled).

The detailed analysis of the volumes of the different lithotypes has been made by levels 25m high (Figures 9 and 10). Compared to the geological model, it appears that the sampling using boreholes on 100m spacing guarantees maximum reduction in uncertainty. Use of boreholes on 200m spacing boreholes leads to an average uncertainty of about 10%, rising to 20% for some levels.

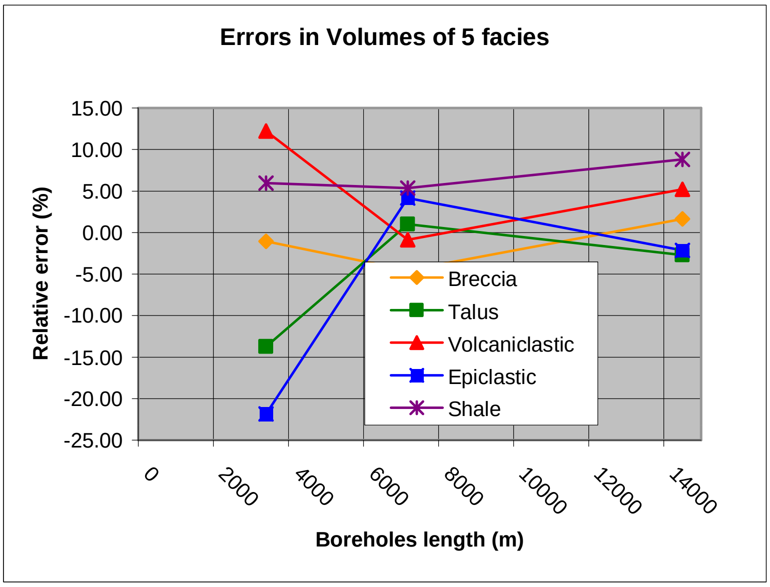

Figure 8: Relative errors on the global volumes from simulations preformed with increasing sampling by boreholes.

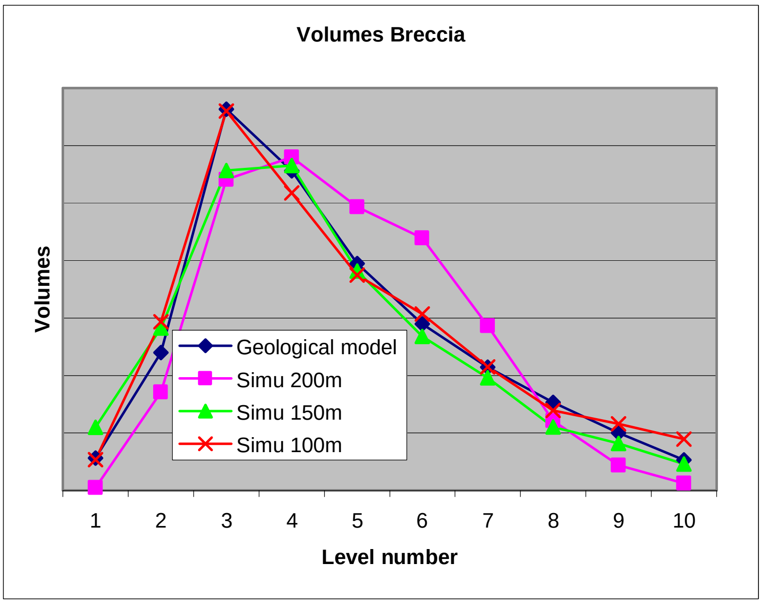

Figure 9: Volumes of Breccia on 25m high levels, of the geological model and the simulations with different sampling

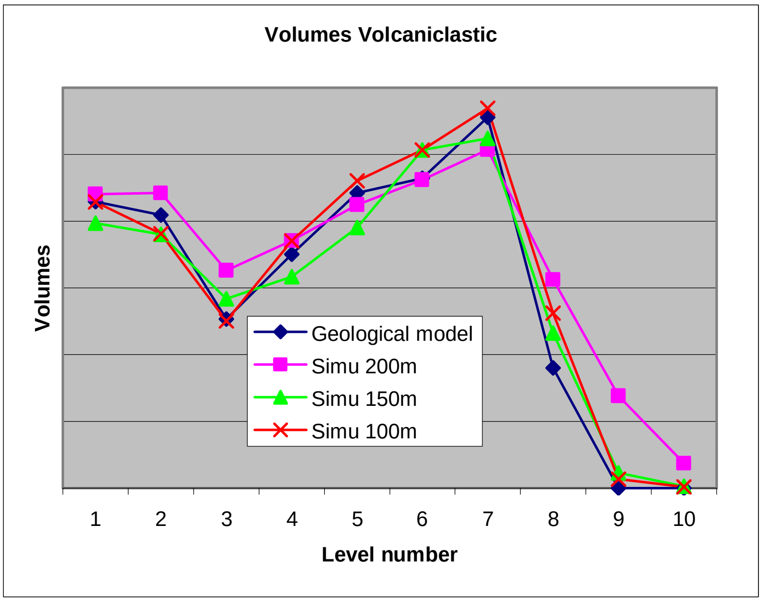

Figure 10: Volumes of Volcaniclastic, on 25m high levels, of the geological model and the simulations with different sampling.

7 Conclusions

The plurigaussian simulation process has proved to be very efficient in providing images reproducing the main features of the geology encountered in kimberlite crater deposits. It appears this may be a useful addition to the process of geological modelling. This will be explored in an operational context. Besides, the quantification of the confidence as a function of the number of holes will aid in economic decision making.

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