Ore reserve valuation of mined-out areas and remnants at East Rand Proprietary Mines (ERPM)

by C. Mosoane* †Paper written on project work carried out in partial fulfilment of B.Sc. (Eng.) (Mining) degree

Synopsis

ERPM was formed in 1893 and as a result of its age, a large volume of data exists in a paper-based format and it was decided to electronically capture data in one of two critical mining areas—namely at Far East Vertical (FEV) Shaft Area (Lower Areas) and Hercules Shaft Area (Upper Areas). The life of mine is dependent on tonnage and grade from these areas. Geostatistical evaluation of the gold reserves has been applied on an *ad hoc* basis in the Hercules Shaft Area and on a continuous basis in the FEV area. This is the first evaluation using geostatistics that was performed on the Upper Areas. This paper is based on the premise that regardless of cut-off grades, geostatistical estimation (kriging) estimates and locates reserves better than 'traditional' methods e.g. polygonal method, inverse squared distance method and it endeavours to estimate and locate the high grade reserves in the Main Reef Leader of Upper Areas.

Introduction

The East Rand Goldfield

Gold on the East Rand was discovered in 1888, only two years after the commencement of mining on the Central Rand. The East Rand goldfield extends from the towns of Benoni and Brakpan south-east towards Nigel and Heidelberg. Since most of the mineral rights in the east Rand were State owned, mine development proceeded in accordance with a lease arrangement in which private enterprise provided capital, technical expertise and management, while the government retained the right to mine. The East Rand goldfield has been the most productive entity to date within the Witwatersrand Basin, having produced over 9500 t of gold metal; it was also an important uranium producer. At present, the goldfield is largely worked out with the exception of E.R.P.M. Ltd which was liquidated and closed in the mid-nineties and re-opened by new management at the end of 1999.

Location

ERPM is located within and near the northern margin of the Witwatersrand Basin in the town of Boksburg, 25 km east of Johannesburg, South Africa. The lease area totals some 95 km^2.

The company is responsible for the mining and recovery of gold in two production units. The central unit consists of relatively shallow remnant pillar mining around the Upper (Hercules Shaft) Areas and the south-eastern unit consists of conventional longwall mining in the Far East Vertical (FEV) Shaft Area.

The Upper Areas are mined at depths down to 2000 m below surface and the Lower Areas are mined at depths of between 2600 and 3200 m below surface.

Not only are the mining methods in the two areas different, but also the geology. At FEV, only one reef (composite reef) is mined and very distinctive hangingwall and footwall lithologies are present while at Hercules, a package of conglomerates is mined within an interval of 0-20 m.

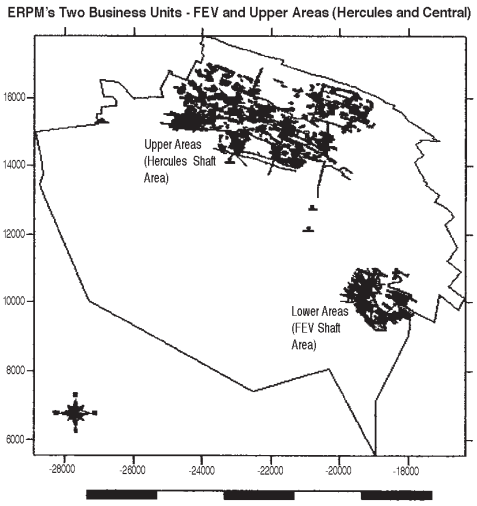

Figure 1—The two production units at ERPM—the Upper Areas and the FEV Area

* *Samancor Chrome, (BHP Billiton), Steelport.*

† *University of the Witwatersrand, Johannesburg.*

Regional geology

ERPM's mining focus is on conglomeratic reefs (South Reef, Main Reef Leader and Main Reef) in the Upper Areas and on the Composite Reef in the FEV Area. Future tonnage contribution will be sourced from the Main Reef Leader (55%) and the sedimentologically complex Main Reef (45%) in the Upper Areas. The more laterally persistent South Reef/ Composite Reef in the south-eastern section of the mine will be the sole contributor of tonnage in the Far East Vertical Shaft Area.

Geologically, the East Rand goldfield is an extension of the Central Rand and contains all the same units. The Central Rand goldfield is located around Johannesburg and extends for a distance of 40 km from Roodepoort in the west to Boksburg in the east.

The principal auriferous conglomerates of the Central Rand are well developed in the west, where they are characterised by partings of about 1 m between the Main Reef and Main Reef Leader, and 30 m between the Main Reef Leader and the South Reef.

Towards the east, the reefs merge progressively and at E.R.P.M, the lower two reefs are completely cut out by the South Reef.

The lowermost Main Reef is generally a poorly sorted conglomerate with pebbles of up to 5 cm in diameter. The Main Reef is the most prolific gold producer in the Central Rand. It is better sorted and graded but thinner than the Main Reef Leader. Pebbles are, on average, coarser being up to 8 mm in diameter. The reef is often dark in colour, mainly due to chlorite in the footwall. The South Reef is the most persistent of the conglomerate layers but is of slightly lower grade than the Main Reef Leader. It is less well sorted than the other two reefs and generally occurs as a number of individual pebble bands with arenaceous partings. Although many dykes and faults have been identified in the lease area, geologists have been able to compile reef contour plans defining future mining blocks with confidence.

The regional distribution of high-grade areas at ERPM is restricted to two broad zones, the Central Payshoot and the Northern Payshoot—the latter has been extensively mined out. The Central Payshoot is projected to extend south-eastwards as far as and beyond the Van Dyk/Sallies boundary (neighbouring mines).

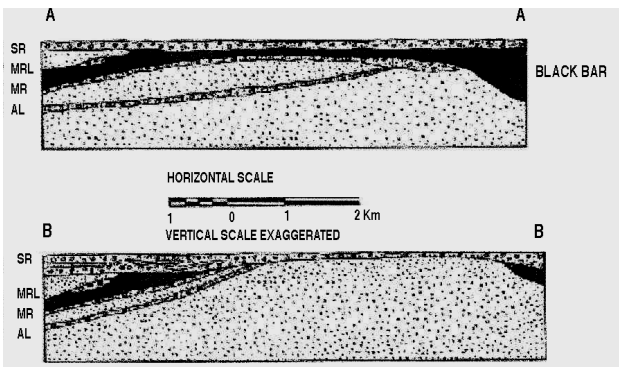

Figure 2—A cross-section of the South Reef, Main Reef and Main Reef Leader coalescing to form the Composite Reef

Over the next eight years the Composite Reef will be the major tonnage contributor and thereafter the Main Reef, Main Reef Leader and to a much lesser extent the Kimberly Reef ore will predominate.

Analysis method

History of evaluation practice at ERPM

The Hercules Shaft Area is structurally complex and care was taken not to combine reefs duplicated by thrusting during the capturing of the data. The Main Reef and Main Reef Leader are separated by an interval of 0–20 m and when they merge, they are called the Composite Reef.

The different reef types were captured separately. Mining blocks defined by remnants were upgraded from resources to reserves not only based on confidence of grade but also on distances between the reefs. At ERPM, the standard is to allocate grades in the remnant areas by allocating arithmetic average grades of perimeter sampling. Commonly employed estimation techniques, such as inverse-squared distance techniques, use a weighted average of sample values to estimate the mining blocks of a deposit. The simplest approach, the polygonal method, which assigns a central sample value to the block, has sometimes been replaced by procedures that also take account of the neighbouring samples outside the block, such as weighting by the inverse of the sample distance from the block. Because of this correlation, samples external to the block boundaries may reveal information about the block.

However, even with such methods, which show a decrease in correlation with distance, it has never been clear why weighting by inverse distance or some other factor such as inverse distance squared, should be used—or to what distance from the block the weighting system should be applied. Furthermore, there was no way of telling how good the estimates were. Frequently, the results from these rather arbitrary estimation techniques were only resolved by 'experience factors' derived after a period of mining when the true block grades did not correspond with expectations.

The application of kriging methods and computer technology to mineral deposit valuation is gaining momentum because of the increased accuracy and speed of valuation that these techniques afford. This paper is restricted to an analysis on the Hercules Shaft Area since an appropriate method of geostatistical analysis has not yet been devised for this area.

Collection, verification and preparation of data

Data capturing (digitizing)

Digitizing is the process of transforming paper graphics (maps, graphs, pictures), graphic files and data into a digital format usable by other computer applications.

A program called 'Didger 2' was used to capture data from 1:1000 mine plans and assay tracings which contained details of *Channel Value* (cmg/t) and *Channel Width* (cm). 'Didger 2' is a highly accurate digitizing program and can precisely transform points, lines or areas from paper maps, graphs, aerial photos, scanned images, graphic files and other plotted information into a digital format than can easily be exported and used in other software.

The data was digitized with a tablet and puck. Tablet calibration establishes the correspondence between the tablet's co-ordinate system and the map's co-ordinate system. When the tablet calibration is completed, 'Didger 2' can translate the puck tablet co-ordinates into map co-ordinates and incorporate those digitized co-ordinates into the project.

Data preparation

The digitized information was exported to Microsoft Excel and printed out in order to check for:

- duplicates
- outliers (in terms of co-ordinates and values)
- obvious mistakes
- zero values—if not part of population, remove.

Once the data was checked, it was sorted into a format that would be recognized by Clark's 'Geostokos Toolkit' which was used to statistically analyse the data.

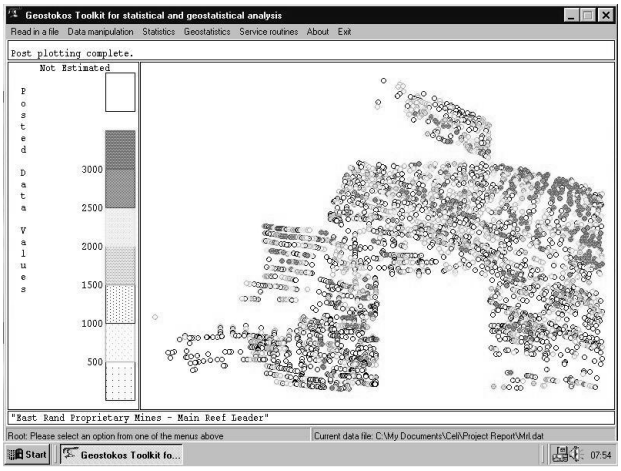

Figure 3—A postplot of the *Channel Value* showing the distribution of cmg/t

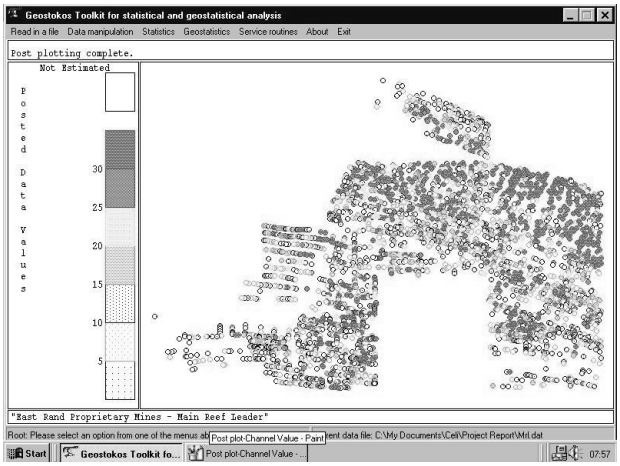

Figure 4—A postplot of the *Channel Grade* showing the distribution of g/t

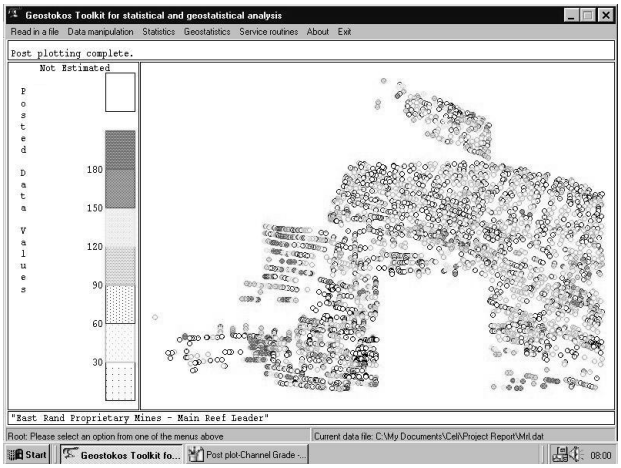

Figure 5—A postplot of the *Channel Width* showing the distribution of thickness

Postplot

Postplots of the data were generated and then printed to facilitate easier visual analysis. The purpose of the postplot is to:

- look for trends
- identify low- and high-grade areas
- get a co-ordinated map
- explain the geology.

The results of the postplots are shown in Figures 3–5:

Observations

Channel value (see Figure 3).

- High channel values are present in the far east and south-west; these are associated with the high channel grades in the same area.
- Lower values are present in the north-west.

Channel grade (see Figure 4)

- There are evenly distributed high-grade areas, especially in the north-east to the north-west and south-west.

Channel width (see Figure 5)

- High channel widths exist in the west but widths are generally low in the east.

Statistical analysis of population

The statistical analysis is the process by which a population is allocated a distribution category—normal, lognormal or three-parameter lognormal.

At first, a histogram was generated in order observe the symmetry of the distribution. Most frequency distributions are either symmetrically spread around the mean or skewed in a certain direction. The 'skew' of a distribution is the extent to which it departs from symmetry throughout the range of scale values. A distribution without any skew is symmetrical. Gold, silver, uranium and other precious metals' distributions are frequently positively skewed and this was true for *Channel Grade*, *Channel Value* and *Channel Width*.

After that, a probability plot was generated. When sample values come from a highly skewed distribution, the

probability plot results in a curved line rather than the ideal straight line which is diagnostic of a normal distribution. The definition of a lognormal distribution is that the logarithms of the data follow a normal distribution. This may be extended by adding a constant before taking the logarithms (three parameter lognormal), but the principle remains. If the logarithms (with or without an additive constant) are normal, the mean and standard deviation of the logarithms can be estimated as with any normal distribution.

The *Channel Grade* and *Channel Width* were lognormal (i.e. the probability plot yielded a straight line), *Channel Value* needed an additive constant before the probability plot generated a straight line (i.e. three parameter lognormal).

Geostatistical analysis of population

Experimental and model semi-variograms

The geostatistical analysis is the process by which a semi-variogram is allocated a model and this model is cross-validated for 'closeness of fit.' Firstly, experimental semi-variograms were generated, in different directions, in order to check that the ranges of each were almost equal. The chosen directions were 0, 45, 90 and 135 degrees and since all the ranges were approximately equal, this meant that each population was isotropic. These populations could then be allocated omni-directional models which consider all possible directions. This process is time-consuming and is open to interpretation and hence, can lead to inaccuracies. The exponential and spherical models were chosen since they both have sills—in the end, the spherical model was chosen for the *Channel Value* and *Channel Width* while the exponential model was chosen for the *Channel Grade*.

The plots of the model semi-variograms are shown in Figures 6–8.

Cross-validation

The main difficulty with any estimation technique is that it is almost impossible to see if the estimated value and the actual value are close to one another or not. The model semi-variogram provides a graphical and numerical measure of the continuity of the mineralization in the deposit. Different semi-variogram models could be fitted but it is important to know which is appropriate.

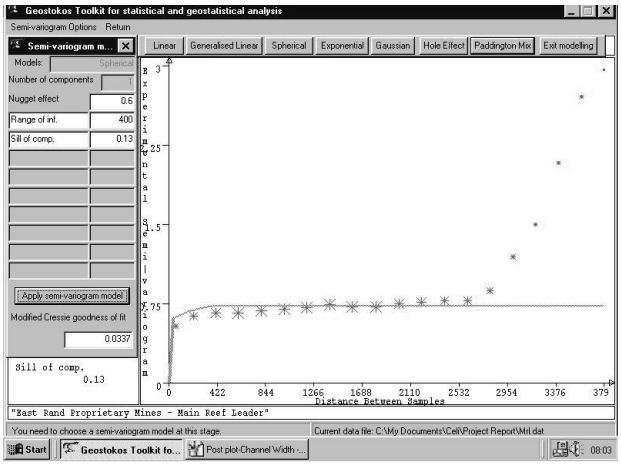

Figure 6—The spherical model semi-variogram on the *Channel Value* data

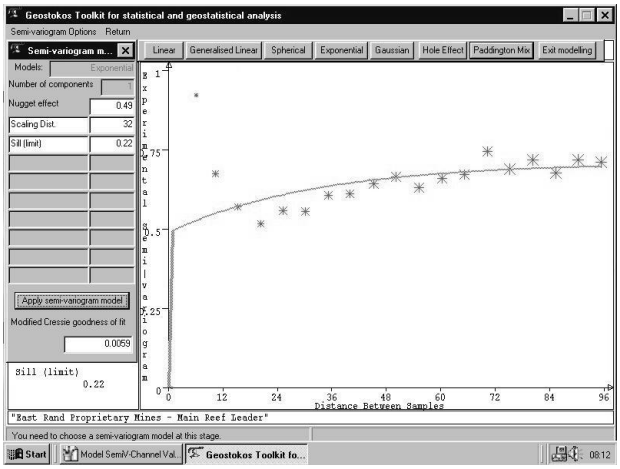

Figure 7—The exponential model semi-variogram on the *Channel Grade* data

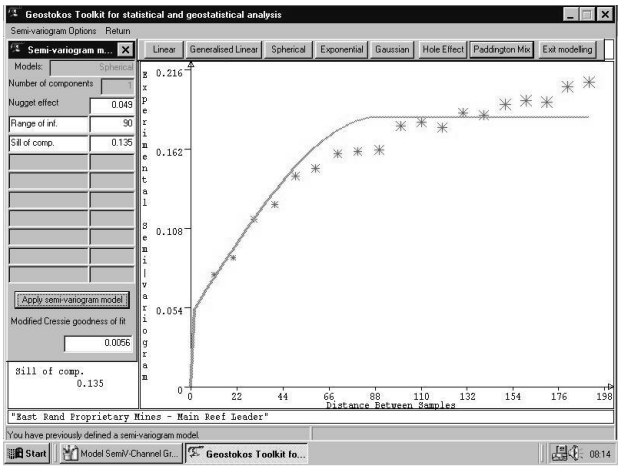

Figure 8—The spherical model semi-variogram on the *Channel Width* data

Cross-validation is a method of justifying the choice of a model. With this approach, a partial data set is used to estimate values at actual sampled locations. 'Real' and 'estimated' values are then compared in such a way that the model can be accepted or rejected. For the cross-validation of a model to confirm the 'goodness of fit'—the average error statistic must be approximately equal to zero and the standard deviation error statistic must be approximately equal to one.

The cross-validation results are shown in the following Table.

	Average error statistic	Standard deviation error statistic
Channel Value	0.00093398	0.8976
Channel Grade	-0.0115	0.9305
Channel Width	-0.0017	0.9433

This cross-validation exercise yielded average error statistics close to zero and standard deviation error statistics approximately equal to one (see above). The models were hence accepted as being true.

Kriging

Geostatistical estimation techniques, based on a study of the spatial variability of the orebody as reflected in the semi-variogram, are superior because they allow calculation of a measure of the error associated with the estimates, namely the variance of the error distribution. It is also possible to find the set of weighting coefficients for a given block and data configuration that minimizes this estimation variance. This procedure, which yields the best linear unbiased estimator, is known as 'kriging'. In other words, kriging is an estimation technique that employs the semi-variogram to give the smallest standard error.

The *advantages* of kriging:

- The estimation technique is tailored by our interpretation of the geological environment as quantified in the semi-variogram model.
- The standard error provides an estimation of how good or bad the estimator is.
- It combines the variance-distance relationship between or amongst the samples.
- It accommodates clustering and poor distribution of samples.
- Kriging automatically compensates for distribution and optimizes the weights that various samples get as well as ensuring that the weights add up to one.
- It allows for size and shape of the samples.
- It honours the data points because the locations of all points are known.

The *disadvantages* of kriging:

- The estimation method is tailored by our interpretation of the geological environment and as quantified in the semi-variogram model. There is no way of determining whether the semi-variogram is right or not.
- You can only use it if there is no trend.
- The regression effect is present so long as you use a weighted average—the high grades are over-estimated and the low grades are under-estimated.
- Highly skewed data causes problems.
- Smoothes the data.

The kriging results are shown in Figures 9–11.

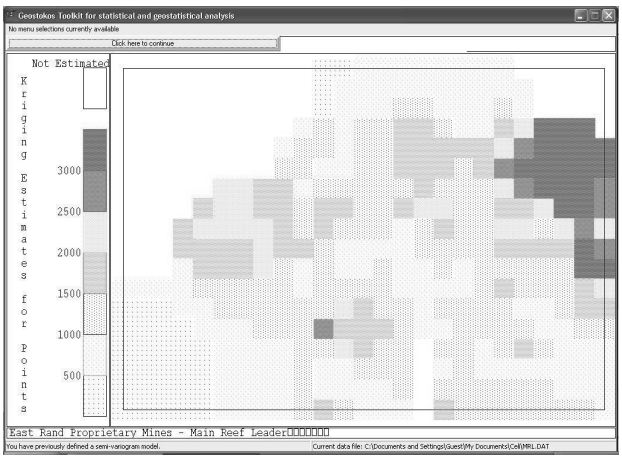

Figure 9—Kriging results for *Channel Value*

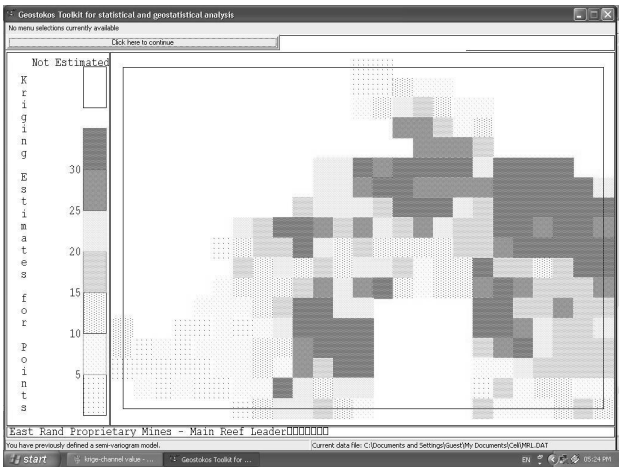

Figure 10—Kriging results for *Channel Grade*

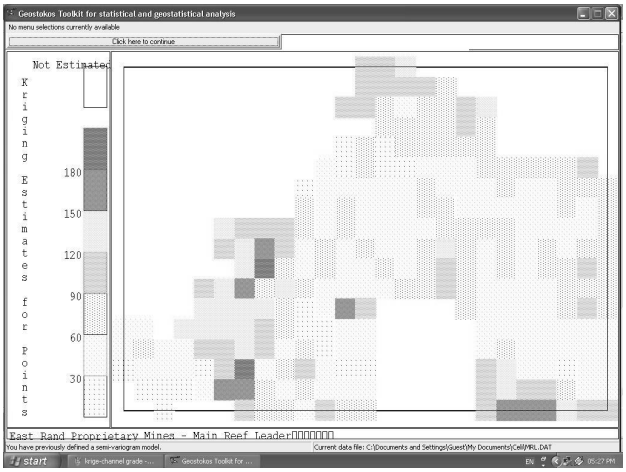

Figure 11—Kriging results for *Channel Width*

Discussion of results

There is good correlation between the postplots and the kriging results.

Channel Value (see Figure 3 and Figure 9)

- High channel values are present in the far east and south-west, lower values are present in the north-west.

Channel Grade (see Figure 4and Figure 10)

- There are evenly distributed high grade areas, especially in the north-east to the north-west and south-west.

Channel Width (see Figure 5 and Figure 11)

- High channel widths exist in the west but widths are generally low in the east, there are some high channel widths scattered towards the east.

Conclusions and recommendations

This analysis is by no means complete! To ensure that a theoretically correct method such as kriging is accepted by the mine, it is important to prove that the results are at least

as good as those obtained by a more traditional method. The geostatistical method described is used to predict the ore values *in situ*. The only other reliable independent estimate of the ore values is obtained from the surface plant, where the tonnage and grade of the mill feed are known with considerable precision. After some consultation with the Survey, Geology and Planning Departments at the mine, the cut-off grades must be established so that grade-tonnage curves can be plotted. These will enable important decisions to be made about which remnant blocks can be extracted economically and which should still be left underground. It is important that the data are analysed separately in terms of reef types, therefore a similar study must be done for the Main Reef and South Reef (where it occurs). This will enable better analysis of each remnant block since it is composed of several reefs in the Hercules Shaft Area. The block sizes for each block were not known and the kriging sizes were selected by default—once these are known, the kriging results will be closer to the truth. The kriging results confirm the position of the high channel grade, value and width areas, therefore, the geostatistical analysis is successful—enough can be deduced to locate and extract the reef.

Also, other kriging methods like universal kriging or random kriging can be assessed for better results. The mining method in the Hercules area is 'undefined' and the channel widths vary considerably because of the change in reef composition. Presently, remnants are being extracted randomly as they are being discovered, so once a standard method or width has been allocated, a better geostatistical analysis can be performed since panel lengths/block sizes will be known. With more time, better models can be chosen whose cross-validation results are closer to the 'fit.' The methods of sampling in the Hercules area can also be improved upon. Each reef must be sampled separately and continuously to facilitate more effective analysis—ERPM is in the process of setting up a dedicated Mineral Resources Management Department which will aid in the continuous monitoring and valuation of the Hercules area.

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SAIMM Gold Medal Awards

For many years the Chamber of Mines awarded a Gold Medal and a scholarship for graduate studies in mining or metallurgy or Engineering at Witwatersrand and Pretoria Universities. At each university the top student in mining or metallurgy and the top engineering student were awarded the scholarship and presented with a medal. During 2000 the Chamber of Mines discontinued its support for these scholarships and the Minerals Education Trust Fund briefly stepped into the gap. However, the Trust's function is not one of providing scholarships hence the South African Institute of Mining and Metallurgy sought the support of the major mining companies so as to continue with these significant awards.

In 2001 and in 2002 these awards to the top students in the fields of mining or metallurgy and engineering were offered through the SAIMM and with the generous support of the following ten companies:

- Anglo American plc
- Anglogold
- Anglo Platinum Corporation
- Avmin
- BHP-Billiton SA
- De Beers
- Goldfields of SA
- Impala Platinum
- Kumba Resources
- Sasol Mining

The SA Institute of Mining and Metallurgy as representative of the industry's professionals is sincerely appreciative of the support from these companies. Through these awards the mining industry is making a meaningful contribution to the development of excellence in the industry though the further development of deserving students at both Pretoria and Witwatersrand Universities. These graduates will have specialized skills that can lead the way for technical developments in the future industry; such developments will have meaningful impact upon the safety and cost effectiveness of mining in South Africa. ◆