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Use of a reorientation strategy for geostatistical ore reserve estimation of a complex dipping tabular orebody as an aid to open-pit mine planning

by OMER MOL,[1] Associate Member and A. D. STEWART GILLIES,[2] Associate Member

ABSTRACT

An evaluation method for a complex dipping tabular orebody is introduced using an iron deposit, the Main Orebody on Koolan Island in the north-west of Western Australia, as the case study. The method involves the use of a reorientation strategy to convert the deposit to a simple flat lying orebody, performance of geostatistical analysis for estimation of sub-blocks, and finally estimation of bench block values. A mineral inventory file which contains bench block location co-ordinates, ore tonnage and block grades, is produced. This information is then used to determine grade-tonnage curves both for individual benches or a series of benches within some defined pit limits.

A comparison between the estimated bench block values and the actual values, obtained by simply averaging the blasthole sample values within the bench block, is also made. The results of this comparison show that the evaluation method produces reliable estimates of the actual bench block values.

Keywords: *Geostatistics, grade-tonnage curves, iron ore, open-pit mine planning, ore reserve estimation.*

INTRODUCTION

A number of iron orebodies on Koolan Island in the West Kimberley Division of Western Australia are operated by B.H.P. Minerals Limited, a wholly owned subsidiary of the Broken Hill Proprietary Company Limited. The island is situated approximately 130 km north of Derby as shown on Fig. 1.

The orebody considered in this paper is the largest of the orebodies (the Main Orebody) on the island. The structure of this orebody is complicated, with varying dip, and the presence of low-grade pods within the ore formation. The lack of drill hole sample data at depth, the existence of low-grade iron ore in the footwall contact zone, and the need to express reserves as bench blocks as an aid to open pit mine planning, make the application of the traditional approaches to ore reserve estimation difficult.

The evaluation method, described in this paper, involves a critical analysis of available exploration drill hole data and other geological information, and the establishment of reorientation strategy for geostatistical structural analysis. Simple kriging is used to estimate sub-block values, which are then used, after reorientation to the original co-ordinate representation, to estimate bench block reserves and to produce an orebody mineral inventory file. This information is used to produce bench plans, grade-tonnage curves for benches and for the whole orebody within a defined pit. In the development of this method, the main orebody is used as a case study. The method is not currently employed by the Company operating the deposit.

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[2] Graduated from the University of New South Wales, B.E. (Mining Engineering) in 1973 and Ph.D. 1978. Since then he has been an Assistant Professor of Mining Engineering at the University of Missouri and is presently a Lecturer in Mining Engineering at the University of Queensland with research and teaching interests in the fields of mining economics and mine ventilation. His address is University of Queensland, St Lucia, Queensland.

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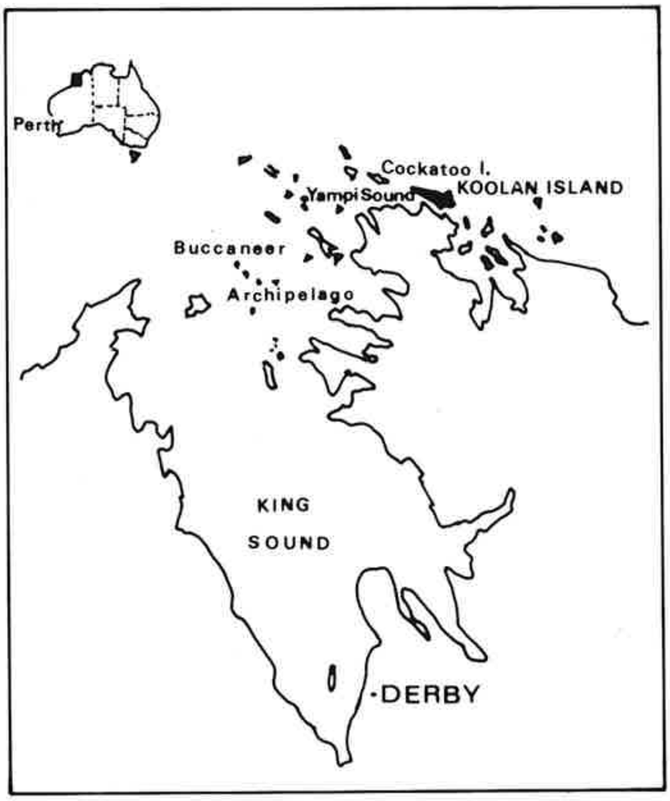

FIG. 1—Location of Koolan Island off the north-west coast of Western Australia.

The Main Orebody is approximately 2000 m long and has an average true thickness of about 30 m. The dip of the orebody varies from 45° at the western end to 65° at the eastern end. The strike is slightly curved with an overall direction from south-east to north-west.

Iron ore has been mined from the Main Orebody since 1965 at an annual production rate of about 2.0 million tonnes. All material is sold as direct shipping ore which has had average grades over the mine life of about 67.0 per cent Fe, 3.0 per cent SiO_2 and 0.7 per cent Al_2O_3. The orebody is mined by an open pit mining method, with a design bench height of 12.0 m. At present, all ore in the upper benches has been mined to a reduced level (R.L.) of 62 m above sea level and some mining has more recently occurred on the R.L. 50 m bench.

In this study, the evaluation of reserves has been restricted to iron formations occurring from the R.L. 50 m bench down to a projected R.L. −58 m bench, this being the lowest planned depth of the open pit.

GEOLOGY AND EXPLORATION DATA

Geology

The geology of the area and the orebodies on Koolan Island have been described in detail by many authors including Canavan and Edwards (1938), Connolly (1959), Harms (1965), Reid (1965), Gellatly (1972), and Gellatly and Sofoulis (1973).

The Main Orebody and the four other minor iron deposits of Koolan Island, as shown on Fig. 2, occur as steeply dipping overturned beds that are conformable with the overlying schists, phyllite, quartzite and the underlying hematite-quartzites. The iron ores consist of fine to medium grained hematite and hematite rich quartzite-sandstone. Some localized conglomerate is present in ores and this contains either pebbles or cobbles of quartzite and hematite-quartzite, and has cavities where the pebbles have been leached out, as explained by Gellatly (1972). It has also been noted that the leaching of interstitial silica from silica-cemented hematite ore have produced fine grained uncemented hematite ore. It has been suggested that the ores have formed through concentration of detrital iron minerals by reworking and winnowing on an ancient beach or sand bar.

The Koolan Island mine grid system was established for convenience, by rotation of the Ausralian grid system through an angle of 30° 10′ 38″ from north. The strike of the Main Orebody lies along an east-west axis with a dip to the south.

Exploration data

The available data on the Main Orebody consists of borehole information from percussion and diamond drilling in which iron formation intersections have been sampled at mostly 2.0 m vertical intervals. The drilling programme was undertaken during the period 1974 to 1980 for exploration and grade purposes. Samples taken were assayed for iron and impurities such as silica, alumina and phosphorous. In this paper the grades of iron, silica and alumina have been considered for evaluation purposes.

Grade drilling practices have been examined (Anon., unpublished company report, 1980), and in particular it has been noted that during percussion drilling some caving and sample contamination occurred in some portions of the holes due to the presence of "running fines". Diamond drilling which later replaced percussion drilling of the orebody formation, gave an average recovery of 75-90 per cent. Core loss has been attributed to the occurrence of hard and soft bands in the ore formation.

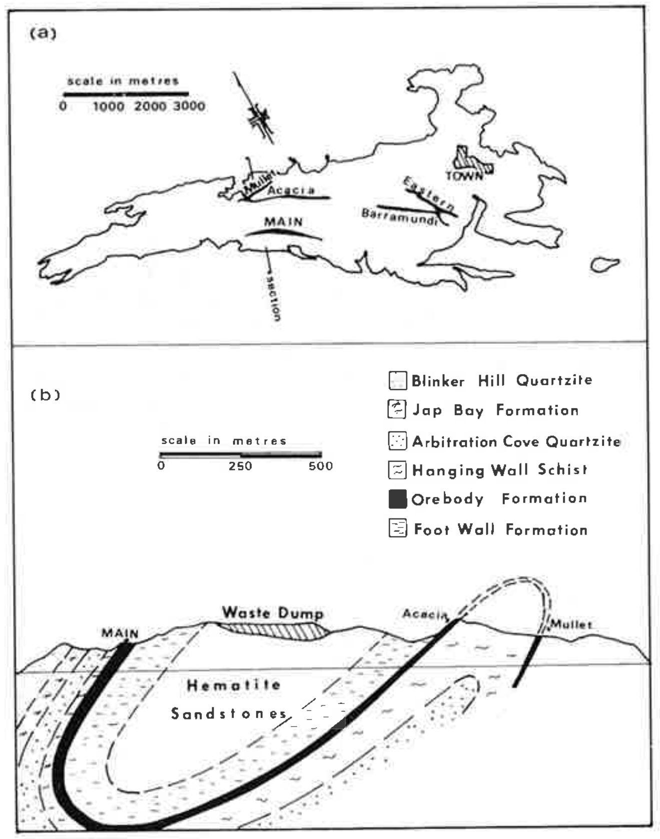

FIG. 2 – Koolan Island iron formations and a cross-section showing typical geological structure.

Refining of the sample data

All borehole sample data were checked and where necessary modified and put on the same representative basis. Samples representing borehole vertical lengths of less than 0.8 m were discarded, and those from lengths of greater than 3.0 m were divided into 2.0 m vertical length increments and average sample grades allocated to them. The sample information in this refined form was stored in a computer data file for subsequent analysis and evaluation. This file contained 2589 data points in a format specifying sample co-ordinates and the sample grades of iron, silica and alumina.

CLASSICAL STATISTICAL ANALYSIS OF DATA

A statistical analysis of the sample data was undertaken to gain some understanding of distributions of sample grades and sample point locations.

Sample grade distribution

The statistical analyses of iron, silica and alumina grades were undertaken using a computer program. Mean grades of iron, silica and alumina with their corresponding variances, standard deviations and skewnesses are shown in Table 1.

Sample location distribution

A sample location distribution highlights the scatter of data points both along the strike of the deposit and at depth. The following points were concluded.

1. The distribution of sample points along strike (Fig. 3), confined between the mining pit limits, appears to be reasonably uniform.
2. The distribution at depth (Fig. 4) is, however, not uniform. It is found that 85 per cent of the total sample points lie between R.L. 88 m and R.L. 2 m. This, of course, highlights the problem of lack of data at depth. The distribution indicates a bimodal characteristic with a major mode on R.L. 62 m bench and a second much smaller mode on R.L. −58 m bench. The existence of even a small number of sample points at depth assists in determining the orebody structure using linear interpolation.

THE EVALUATION METHOD

Using the dip angle information and a reorientation strategy, the orebody is converted to a flat lying tabular form deposit. Geostatistical analysis is then applied to produce kriged estimates of sub-blocks which form the basis for calculation of the bench block values. From the bench block information it is possible to produce grade-tonnage curves for individual benches and the whole orebody within specified pit limits.

TABLE 1
Classical statisatics of exploration drill hole sample grades

	Iron (%)	Silica (%)	Alumina (%)
Mean	63.387	6.489	0.638
Variance	128.319	155.553	2.325
Skewness	−2.410	2.497	1.525
No. of samples	2581	2433	2482

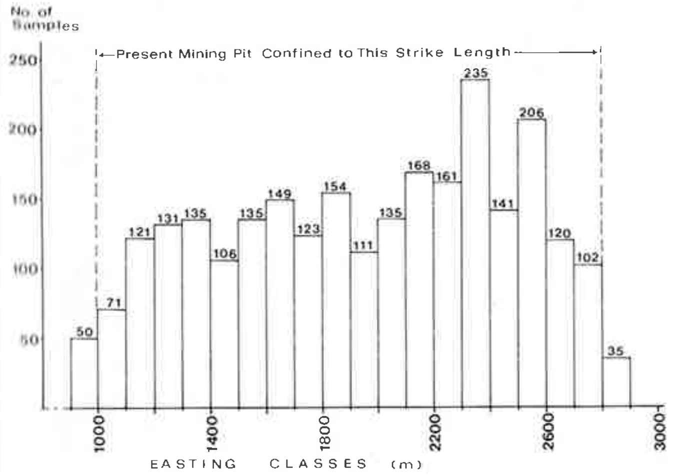

FIG. 3 – Histogram showing distribution of 2589 drill hole samples within easting section classes.

Reorientation strategy

Formation dip angles

The dip angle of the orebody formation can be ascertained by producing cross-sections along the strike from the borehole information. Association of this knowledge with other possible information from the mined out sections of the existing pit can be used to classify the orebody along strike into regular or irregular sections with a dip angle representing each section. Assumptions made in this procedure were that the dip angle is constant both within each incremental section along strike and also uniform within the range of depth considered. Table 2 shows the dip angle determined for each section along strike. In this procedure, advice from the company geologist on the island was used to support interpretation from cross-sectional representations.

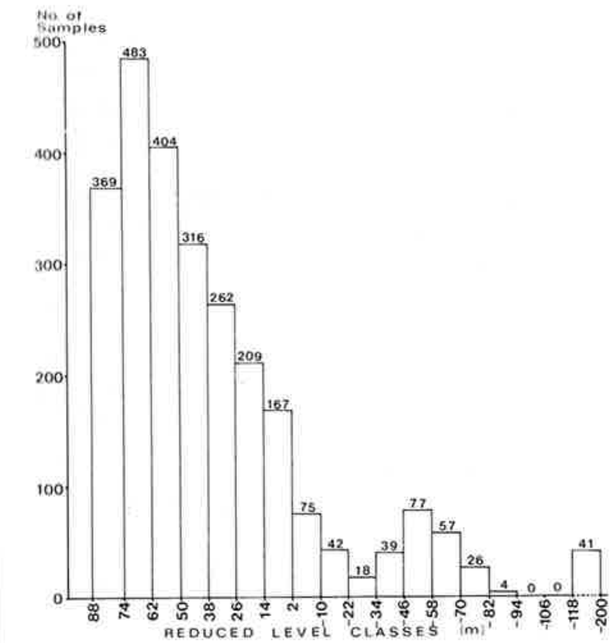

FIG. 4 – Histogram showing distribution of 2589 drill hole samples at depth in Reduced Level classes.

TABLE 2
Section classes along strike and orebody formation dip angles

Section classes (Eastings) from	to	Formation dip angles (%)
900E	1450E	46
1450E	1550E	47
1550E	1650E	49
1650E	1950E	50
1950E	2050E	51
2050E	2150E	53
2150E	2250E	54
2250E	2350E	55
2350E	2550E	56
2550E	2650E	58
2650E	2900E	63

Rotation of the orebody

The iron orebody was originally deposited as horizontal bed formations, prior to intense folding of the area. The bedded nature of the mineralisation suggests that the variability of grade distribution along bedding planes should be small. To make use of the depositional characteristics of the orebody, a model was developed which rotates the formation to its original flat lying tabular form.

The sample data points were rotated by their corresponding dip angle in the following manner. As exploration drilling was mostly undertaken at 25 m intervals, the drill hole samples were brought onto regular cross-sectional planes at 25 m intervals using a computer program. The maximum distance any sample had to be projected was 12.5 m. Error involved in this projection along the bedding planes was considered to be very small. All sample data on the same cross-sectional plane are designated with the same easting (E) value and are rotated as a group by the appropriate dip angle for that strike section. This procedure was followed for cross-sectional planes at 25 m intervals along strike from 900E to 2900E to include the whole pit. All cross-sectional planes were rotated about the same individual pivot points which fall on a line perpendicular to all the cross-sectional planes. This axis line had cross-sectional co-ordinates of northing (N) 1230.0 and R.L. −170.0 m.

Following the rotation, the orebody was treated as a simple flat lying tabular deposit and geostatistical analysis was applied for estimation of sub-block grades.

Geostatistical analysis

The theory of geostatistics has been described in numerous text books by authors such as Matheron (1971), David (1977), Journel and Huijbregts (1978) and Rendu (1978). Bell and Reeves (1979) reviewed the literature available in English on "Kriging" and "Geostatistics", and provided a list of references in their paper.

Structural analysis

Due to the flat lying bedded nature of mineralization, the orebody was evaluated by dividing the deposit into horizontal slices of 2.0 m thickness. To effectively analyse the structure, the orebody was divided into three zones along the strike as designated. 1. zone one, 900E-1700E, 2. zone two, 1700E-2300E and 3. zone three, 2300E-2900E. Semi-variogram values in four directions (0°, 45°, 90° and −45°) were calculated for each of the horizontal slices and these values were averaged to produce the mean directional semi-variograms of all horizontal slices for each zone for iron, silica and alumina grades.

Experimental semi-variograms were produced and an example of one of these for iron is shown in Fig. 5. The mean directional semi-variograms indicate strong geometrical anisotropy—the anisotropy ratio for the example in Fig. 5 being 2.0. This highlights that the correlation of the grade distribution in the 0° direction is better than that for the 90° direction. A nugget effect was also seen on these experimental semi-variograms which indicates some micro-structural variability. The projection of sample points to cross-sectional planes before rotation would certainly be a contributing factor to the magnitude of the nugget effect. The directional semi-variograms in directions other than 90°, had a minimum lag interval of 25 m. This is to be expected as the cross-sectional planes on which the sample data points were projected were spaced at 25.0 m intervals. The 90° directional semi-variogram, however, provided an indication of the nugget effect for small lag intervals. The fluctuations of semi-variogram values at large distances could be caused both by the macro-structural changes, and to some extent, by possible slight deviation of dip angles used for reorientation, from that which actually occur. Despite this, the experimental semi-variograms showed a reasonably good degree of correlation between sample points. They are fitted simple spherical model semi-variograms to characterize the grade variation. The validity of model semi-variogram parameters was checked by the point kriging test.

Estimation of sub-blocks by kriging

The model semi-variograms are used in the kriging system to estimate the sub-block values within the same 2.0 m thick horizontal slices that had been used for semi-variogram construction. The sub-block size chosen was 25.0 m in the east-west direction, by 10.0 m in the north-south direction with a thickness of 2.0 m. The sub-block grades of iron, silica and alumina were estimated from a minimum of three surrounding sample points within the search radius specified. The kriging results containing the easting, northing and R.L. co-ordinates of sub-blocks with the estimated iron, silica and alumina grades with their associated kriging variances were stored in a computer file.

Following this, the sub-blocks were then rotated back to the original co-ordinate system. Cross-sectional plane interval groups were rotated about the same pivot point and by the same dip angle as had been used for the initial reorientation. With all sub-blocks now represented on the original Koolan Island co-ordinate system, some filtering took place to discard sub-blocks with an R.L. greater than 62.0 m, or less than −58.0 m. The final data file contained 13567 sub-blocks.

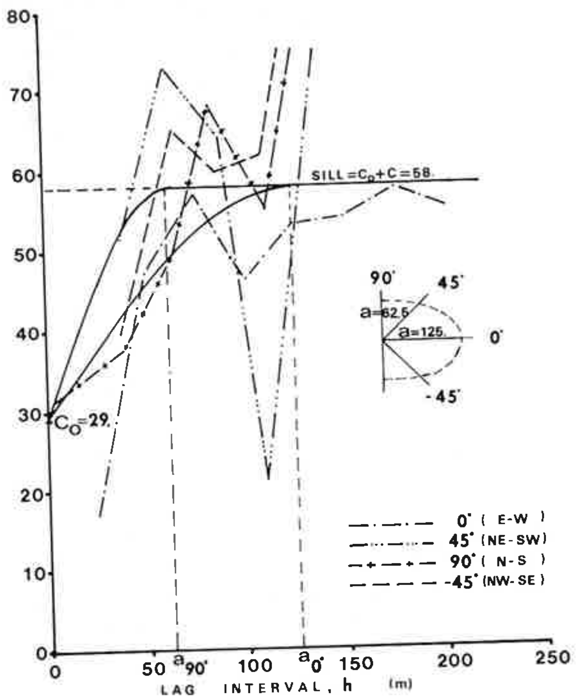

FIG. 5—Mean horizontal directional semi-variograms for iron grade for zone two.

Estimation of bench blocks

The kriged sub-blocks were considered as data points to estimate the bench block values. The following approach was used for the estimation of bench block values.

Bench block size

The chosen size for the bench blocks was 10.0 m in the north-south direction 25.0 m in the east-west direction, and with a vertical thickness, equivalent to the mining bench height of 12.0 m. Fig. 6 illustrates as a cross-sectional view the relationship of sub-blocks and bench blocks to the orebody formation.

Estimation of block values

Individual bench blocks have a number of sub-blocks falling within them as shown in Fig. 6. An arithmetic average of the sub-block grade values within a bench block gives good estimates for the bench block grades. Some bench blocks were found not to have a sufficient number of sub-blocks falling within them. For reliable estimates to be made, a minimum of three sub-blocks had to be present within the individual bench blocks, and accordingly, those blocks which lie at the contact zones, were only included if they met this minimum requirement. For these blocks, the average grades of the sub-blocks which fall within them were used to represent the whole block. A computer program was used for this estimation procedure and output containing the bench block co-ordinates with the estimated iron, silica and alumina grades, and a calculated ore tonnage for each block was stored in a computer file, called "the mineral inventory file". The calculation of the block ore tonnage was undertaken using a specific gravity factor of 4.0 t/m³. This factor was assumed to be constant over the whole iron formation.

The information in the mineral inventory file is available in a form that can be used to aid mine planning in producing bench plans, grade-tonnage curves, and even cross-sections of orebody formation at selected cutoff grades.

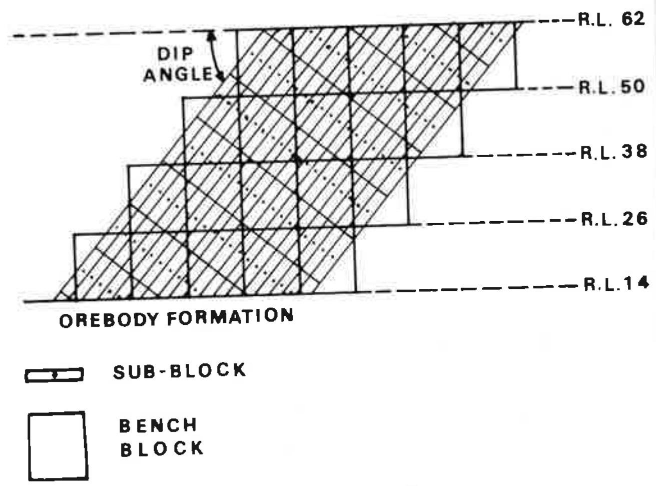

FIG. 6—Cross-sectional view showing the relationship of sub-blocks and bench blocks to the orebody formation.

Reliability of the estimated bench block values

To assess the reliability of the estimated bench block values, a comparison with the actual values for a mined out area may be made. Blasthole sample grades from the mined out section of the R.L. 50 m bench were obtained from the Koolan Island Main Orebody. These were used to obtain actual bench block values by averaging grade information which fell within the dimensions of the block. In this way actual values for 48 bench blocks were obtained for comparison with the estimated grades calculated by the described method. A copy of the print-out of this comparison is attached in Appendix 1 as a table and the results are summarised in Appendix 2. The comparison of results demonstrates that estimated values are very close to the actual grades in all cases with the errors of estimation being low.

The estimated bench block values also help to locate the presence of low grade pods within the orebody, as the presence of waste will give low sub-block values which, when averaged, will decrease the block grade values. Consequently, reasonably realistic values will still be obtained using this method.

The estimated bench block values produced by the described method are in very close agreement with the actual bench blocks in the low grade parts of the mined-out area. This can be seen by comparing the estimated and actual bench block values in Appendix 1. Based on this comparison, it can be concluded that the described method is capable of producing reliable results. However, comparison of more bench blocks, as they become available, will contribute further to the assessment of the reliability of the estimated values.

Application of results: grade-tonnage curves

Bench block values from the mineral inventory file can be used to perform a series of grade-tonnage calculations at selected cutoff grades for individual benches, a series of benches and for the whole deposit. Grade-tonnage curves are of importance in mine planning as they show ore reserve tonnages at given cutoff grades, and mean estimated grades of these reserves. An example of an individual bench grade-tonnage curves for the Koolan Island Main Orebody is shown in Fig. 7.

CONCLUSION

The varying dip angle, presence of low grade pods in the orebody, lack of drill hole sample data, and the need to express reserves as bench blocks for the purpose of open-pit mine planning, make traditional direct approaches to ore reserve estimation difficult for the Koolan Island Main Orebody. In this paper, an evaluation method is described which produces grade and tonnage estimates for bench blocks which compare favourably with actual values obtained from the blasthole samples.

The evaluation method involves a critical analyses of the available data, a good understanding of geology, establishment of a reorientation strategy, application of geostatistical analysis for production of kriged sub-blocks, and estimation of bench blocks to produce the mineral inventory file which contains the co-ordinates, ore tonnage and grades of bench blocks. The method allows full use of all available data from exploration drill hole samples of length greater than 0.8 m, and gives a true picture of the orebody formation by not filtering any samples because of their low grade values. The mineral inventory file can be used to determine bench plans and grade-tonnage curves for individual benches or a number of benches within some defined pit limits.

The developed procedure demonstrates how a complex ore formation can be evaluated for ore reserve grades and tonnages while producing reliable estimates.

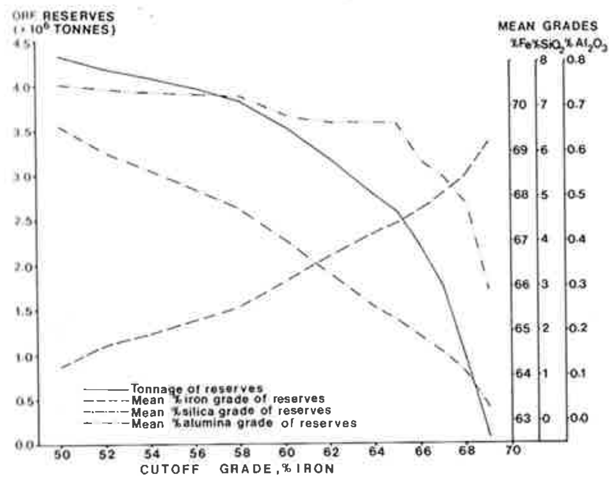

FIG. 7—Grade-tonnage curves for the Koolan Island Main Orebody R.L. 50 m bench.

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APPENDIX 1

Table showing the comparison of estimated and actual block values for 48 bench blocks on R.L. 50 m bench of the Main Orebody, Koolan Island

E	N	R.L.	%Fe			$\%SiO_2$			$\%Al_2O_3$		
			est.[1]	act.[2]	err.[3]	est.	act.	err.	est.	act.	err.
2000.0	1340.0	50.0	68.341	67.650	0.691	1.193	1.275	−0.082	0.486	1.150	−0.664
2000.0	1350.0	50.0	68.609	68.767	−0.158	0.865	0.833	0.032	0.305	0.600	−0.295
2025.0	1330.0	50.0	67.728	68.800	−1.072	1.888	0.775	1.113	0.676	0.500	0.176
2025.0	1340.0	50.0	68.271	68.933	−0.662	1.366	0.733	0.633	0.466	0.467	−0.001
2050.0	1330.0	50.0	68.273	68.625	−0.352	1.348	1.163	0.185	0.535	0.413	0.122
2050.0	1340.0	50.0	67.432	66.740	0.692	2.617	4.067	−1.450	0.379	0.627	0.112
2075.0	1320.0	50.0	68.290	68.467	−0.177	1.358	1.333	0.025	0.548	0.533	0.015
2075.0	1330.0	50.0	68.684	68.614	0.070	0.952	1.057	−0.105	0.459	0.500	−0.041
2075.0	1340.0	50.0	65.916	64.850	1.066	4.980	6.860	−1.880	0.309	0.210	0.099
2100.0	1320.0	50.0	68.507	68.960	−0.453	1.091	0.840	0.251	0.552	0.420	0.132
2100.0	1330.0	50.0	68.780	68.167	0.613	0.864	1.875	−1.011	0.470	0.358	0.112
2100.0	1340.0	50.0	64.601	63.042	1.559	7.167	9.342	−2.175	0.342	0.150	0.192
2125.0	1320.0	50.0	68.435	68.800	−0.365	1.071	0.967	0.104	0.599	0.467	0.132
2125.0	1330.0	50.0	68.803	68.625	0.178	0.780	1.300	−0.520	0.482	0.238	0.244
2425.0	1270.0	50.0	67.613	68.260	−0.647	1.744	1.200	0.544	0.834	0.820	0.014
2425.0	1280.0	50.0	68.783	68.600	0.183	1.099	0.817	0.282	0.375	0.583	−0.208
2425.0	1290.0	50.0	69.062	69.425	−0.363	0.752	0.300	0.452	0.366	0.200	0.166
2450.0	1270.0	50.0	68.424	68.943	−0.519	0.932	0.886	0.046	0.639	0.643	−0.004
2450.0	1280.0	50.0	69.299	69.178	0.121	0.474	0.489	−0.015	0.284	0.300	−0.016
2450.0	1290.0	50.0	68.728	69.167	−0.439	1.204	0.433	0.771	0.290	0.289	0.001
2475.0	1270.0	50.0	68.697	68.840	−0.143	0.751	0.840	−0.089	0.486	0.610	−0.124
2475.0	1280.0	50.0	69.278	69.263	0.015	0.460	0.438	0.022	0.244	0.338	−0.094
2475.0	1290.0	50.0	67.396	68.622	−1.226	2.938	1.300	1.638	0.229	0.244	−0.015
2500.0	1260.0	50.0	67.974	69.386	−1.412	1.585	0.500	1.085	0.661	0.300	0.361
2500.0	1270.0	50.0	68.908	69.456	−0.548	0.631	0.378	0.253	0.380	0.244	0.136
2500.0	1280.0	50.0	69.208	69.557	−0.349	0.449	0.357	0.092	0.244	0.143	0.101
2525.0	1260.0	50.0	68.307	69.227	−0.920	1.335	0.536	0.799	0.610	0.300	0.310
2525.0	1270.0	50.0	69.024	69.567	−0.543	0.605	0.244	0.361	0.351	0.144	0.207
2525.0	1280.0	50.0	69.207	69.000	0.207	0.417	0.583	−0.166	0.244	0.333	−0.089
2550.0	1260.0	50.0	68.569	69.178	−0.609	1.045	0.589	0.456	0.541	0.311	0.230
2550.0	1270.0	50.0	69.082	69.663	−0.581	0.579	0.312	0.267	0.331	0.138	0.193
2575.0	1260.0	50.0	68.401	68.617	−0.216	0.958	0.950	0.008	0.581	0.683	−0.102
2575.0	1270.0	50.0	68.903	69.450	−0.547	0.661	0.388	0.273	0.344	0.250	0.094
2600.0	1260.0	50.0	67.954	69.473	−1.519	1.188	0.364	0.824	0.725	0.236	0.489
2600.0	1270.0	50.0	68.483	69.243	−0.760	0.994	0.414	0.580	0.376	0.243	0.133
2625.0	1250.0	50.0	68.496	69.640	−1.144	1.034	0.200	0.834	0.588	0.140	0.448
2625.0	1260.0	50.0	68.307	69.600	−1.293	0.995	0.242	0.753	0.600	0.150	0.450
2625.0	1270.0	50.0	68.089	69.425	−1.336	1.461	0.325	1.136	0.337	0.188	0.149
2650.0	1250.0	50.0	68.262	69.300	−1.038	1.330	0.400	0.930	0.374	0.233	0.141
2650.0	1260.0	50.0	67.311	69.371	−2.060	2.299	0.386	1.913	0.642	0.229	0.413
2650.0	1270.0	50.0	67.919	69.211	−1.292	1.710	0.589	1.121	0.300	0.222	0.078
2675.0	1240.0	50.0	68.587	69.155	−0.568	1.019	0.636	0.383	0.455	0.227	0.228
2675.0	1250.0	50.0	68.180	69.329	−1.149	1.422	0.500	0.922	0.238	0.143	0.095
2700.0	1240.0	50.0	67.930	68.350	−0.420	1.637	1.190	0.447	0.620	0.670	−0.050
2700.0	1250.0	50.0	68.290	69.238	−0.948	1.268	0.550	0.718	0.309	0.225	0.084
2725.0	1240.0	50.0	66.556	64.600	1.956	2.844	3.788	−0.944	1.012	2.700	−1.688
2725.0	1250.0	50.0	68.209	68.425	−0.216	1.222	1.000	0.222	0.433	0.725	−0.292
2725.0	1260.0	50.0	67.709	68.700	−0.991	2.326	0.600	1.726	0.260	0.500	−0.240

[1] est.—estimated block grade.
[2] act.—actual block grade, obtained from blasthole samples.
[3] err.—error, between estimated and actual block grades.

APPENDIX 2

Summary table of comparison of estimated and actual grad values of 48 bench blocks in Appendix 1

	Iron (%)	Silica (%)	Alumina (%)
Mean estimated grades	68.246	1.436	0.456
Mean actual grades[1]	68.656	1.149	0.416
Mean error	−0.410	0.287	0.040
Relative error	−0.006	0.200	0.088

[1] obtained by averaging blasthole sample grades within bench block.