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Block by block reserve estimation - a case study

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SYNOPSIS

Over the last decade or so, computer methods for planning the 'optimal' open pit for a mineral deposit have grown in usage and in complexity. Almost all of these methods demand, as input, the estimated average value of individual (small) block values throughout the deposit. Thus. in parallel with, but lagging slightly behind, open pit planning methods have come the computer methods for block by block estimation.

Probably the most sophisticated and possibly the most reliable of these block estimation methods is the technique known as I Geostatistics' or the 'Theory of Regionalised Variables'. Almost within the last seven or eight years, this approach has spread throughout the civilised world and is rapidly becoming the undisputed favourite. Many papers have been published showing how geostatistics and kriging techniques are applied to open pit situations. However, these techniques have tended to concentrate on the later estimation stage of a geostatistical analysis. The first stage, that of modelling the deposit being valued, has been glossed over in most of the more recent literature. This paper intends to direct the reader's attention back to this most important stage, and to describe briefly some of the difficulties which might arise in practice. A case study is discussed which involved one of the more common modelling problems.

INTRODUCTION

The growth in usage of Geostatistics (or the Theory of Regionalised Variables) as an ore reserve estimation tool over the last ten years has been quite remarkable. More and more mining companies, consultants and academic centres have begun to use geostatistics as its advantages become widely known and more obvious. Many large computer packages have been brought into use and put on the market. to satisfy the demand for a geostatistical facility from companies unwilling to devote their time to reinventing the wheel. Case studies are published at every major symposium to illustrate the use of geostatistical methods and their superiority over anything previously available.

It is not this author's intention to produce yet another paper with a layman's description of geostatistical concepts, followed by a comparison with 'inverse distance' or 'polygons'[5]. The purpose of this paper is to discuss the current usage of geostatistical techniques to estimate block averages which will be used to design an open pit. This is perhaps the most prevalent use of these techniques within surface mining. It is also the main field to which the development of computer packages has been directed, and hence the main interest of the mining engineer or the project manager. There is an increasing tendency within the industry to purchase or lease such a computer package, and then to assume that it is only necessary to link it to a database, push a button and wait for the computer to print out the 'Best' possible ore reserve. Many consultancy companies also appear to have this kind of blind faith in their computer's ability to produce geostatistical reserve estimates.

The main advantages to using geostatistical methods in ore reserve estimation are two:

1. the first stage of such an analysis produces a . model' of the particular deposit which is under study. All subsequent estimation stages depend completely on this model, and <u>assume</u> that it is absolutely representative of the deposit and/or the economic variables measured within it.
2. the second stage produces reserve estimates using whichever of the geostatistical estimation techniques is favoured by the user. Each estimated value is accompanied by a 'standard error', which indicates quantitatively the reliability of the estimator. That is, confidence limits can be constructed for each estimated value.

The second stage of the process is the one which has been dealt with intensely at. conferences, in publications, in case studies and in computer software development. Many papers will be found in the literature [1 7 9] describing different 'kriging' techniques and how each is better than its predecessor or its competitor. Many papers will also be found extolling the virtues of this or that computational approach to the most efficient application of these techniques[2 6 8]. Thus we have a half dozen different kriging approaches, ranging from 'ordinary' kriging through to the 'multivariate gaussian' approach and we have half a dozen different computer approaches to the problems of estimating three dimensional block values. It is not the purpose of this paper to consider, criticise or compare these various approaches -- all of which have been extensively documented elsewhere. It <u>is</u> the author's considered opinion that too much attention has been focussed upon the second stage of the process to the detriment of the first. It is a little futile to be arguing the merits of this or that computational technique, or the comparative applicability of disjunctive as, against indicator kriging, if the user has forgotten that all of his sophisticated ironmongery depends on his original model of the deposit.

With the advent of the large, almost automatic computer programs there is an increasing tendency to forget that we are dealing with a geologically complex mineral deposit -- and not a nicely rounded, homogenous, stationary statistical entity. The first - and most important -- advantage to geostatistics is its ability (when used properly) to adapt itself to <u>your</u> deposit. Much of the information which goes into the <u>geological</u> model of a deposit is not numerical.

but interpretive or even, sometimes, intuitive. This information should also be incorporated into a geostatistical model[11], but very often cannot − either because the user is unsure how to use it to influence a numerical model, or because the computer system in use is too unwieldy and inflexible to cope with anything other than the simple assay values per drill core section. In fact. many of the current computer packages seem incapable of even dealing with core sections but must go directly to bench or block composites.

The purpose of this paper, then, is to outline some of the problems which arise in practice during the rnodelling of a mineral deposit and to illustrate one of these in some detail. It is necessary to emphasise that geostatistics is (probably) the best way to estimate the reserves in most deposits. However, it is not and never can be a totally automatic computer method. The second stage of the estimation process may be completely automated but only once the correct and appropriate model of the deposit hads been produced by a process which is a blend of geological, geostatistical and computer expertise.

GEOSTATISTICAL MODELLING

The basic assumptions

Before we can build any kind of model, geostatistical or otherwise, it is necessary to make some assumptions about the thing which we are trying to model. With statistical modelling methods these tend to be fairly restrictive mathematical conditions, but most of them correspond to similar assumptions made during the 'physical' interpretation process.

The basic assumption which every modeller must make is that a suitable model exists, and that it is fairly simple. The geologist does this in correlating one borehole with the next; the statistician does this when assuming that data comes from a single probability distribution; the geostatistician does this when assuming that data follows a single semi-variogram. This basic assumption widens out, then, to include the assumption that the mineral values vary in a consistent manner over the deposit. If there are mineral values in two boreholes. there will be mineral values in all the ground between. If there are mineral values in two boreholes, the mineral values in the ground between them will be related to the mineral values in the holes. If there are another two holes somewhere else, these same conditions will apply. These all sound like fairly sensible assumptions, and mostly are. These are the basic assumptions which underly <u>all</u> the geostatistical estimation methods.

Let us consider these sensible assumptions a little more closely, to reveal some of the implications. Whoever is doing the modelling of this deposit has firstly to rely on his original sample data. He must believe that the assay or mineral value shown in connection with a specific drill core section <u>is</u> the assay or mineral value which actually existed within that core section. That is, that the core section data not only reflects <u>a</u> data value within the deposit, but shows <u>the</u> data value <u>at that position</u> within the deposit. This is particularly true with the geostatistical approach, which treats data values as virtually sacrosanct. The reader will find in the literature[4], explanations of how any 'sampling' errors will be incorporated into the 'nugget effect' in the geostatistical model and hence allowed for in the final estimation method. This will be true. but only if the sampling' errors are consistent in their behaviour all over the deposit. That is, there is no correlation between the value of a sample and the likely sampling error; there is no correlation between the depth of a hole and the likely sampling error; data errors are not affected by the sample's position within the deposit; and so on.

With a manual method of estimation, or perhaps a highly interactive computer approach, unreliability of individual sample values could be allowed for – if known about. With an automated technique this would be extremely difficult, unless such blanket assumptions as those described above were brought into play.

The modeller must also assume that his model is valid throughout the deposit. This is not so restrictive or inflexible an assumption, since it is quite possible to break the deposit up into zones within which a single model could hold. These will generally be geological zones: either geological units, bounded by faults or contacts; or mineralisation units where the mineral has been reworked, oxidised or remobilised perhaps. This is fairly common practice[10], though 'zones' still tend to be major portions of the complete deposit. One of the problems which arises in practice is that, if the zones become too small, there is not enough data within each zone to do any modelling anyway!

There are many other questions which must be considered at the modelling stage. What should be done around the edges of a deposit? Should the modeller define a boundary within which the homogenous. consistent 'ore' values lie? Should he use a more sophisticated model and technique at the edges -- where his data is most sparse? Should he differentiate by rock type within his core section data, or perhaps compensate for density if rock types within the deposit vary significantly? How much account should be taken of folding or deformation in any particular deposit? How does he cope with different sizes of sample, e.g. varying diameters of diamond drill core. What happens when samples have been collected by different sampling methods, or have been valued by different techniques?

The remaining portion of this paper will concentrate on <u>one</u> of these problems. No hard and fast solution to the problem will be proposed in this paper, and it is not suggested at any point that this situation would apply to any or every other deposit. This illustration is merely given as an object lesson to those who would follow the automated course of pouring all of the data into the geostatistical petrol tank and then expecting the vehicle to arrive at the correct destination without any steering.

A MODELLING CASE STUDY

The deposit used to illustrate this case study is a base metal sulphide project administered by Shell South Africa (Metals Division). Many thanks are due to them for permission to use the data from the project to produce this study. No detailed geological description will be given. However, a lead/zinc mineralisation in limestone is a common enough type of deposit for the reader to form his own intuitive model for the purposes of this paper. In addition to this paucity of geological information, the mineral values have been adjusted by an arbitrary factor which will not mask the 'geostatistical' qualities of the deposit.

Two methods of drilling were used to sample this deposit: diamond drill coring and percussion drilling. Both types of drilling produce 'core sections' which have been assayed for lead and zinc values. The results from the percussion drilling referred (generally) to one metre sections down the drillholes. The diamond drilling tended to be sectioned according to geological horizons, and within the visible mineralisation may range in length from 40 cm to 4

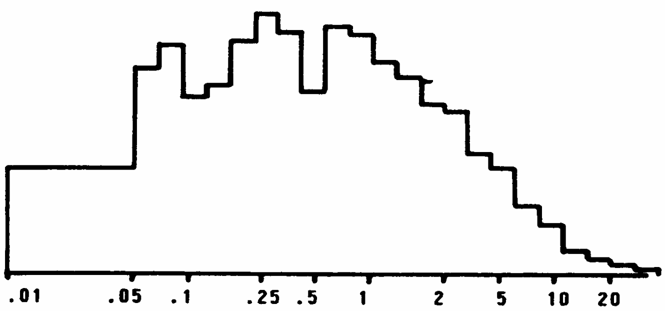
metres. Where drilling showed no visible mineralisation. the cores were not assayed but allocated a threshold mineral value. These cores may be over 50m in length. To avoid confusion, these 'unassayed' cores were omitted from this illustration. However, the results given here still hold if allowance is made for these low grade core lengths. Only vertical drill holes were used for the purposes of this case study, to avoid the need for compensating inclined holes.
This case study has been restricted to a small area within the larger deposit, for various reasons. Firstly, to be sure that modelling has some sound basis, we must be sure that the area under consideration constitutes as homogenous a geological unit as possible. No fringe effects from the edges of the mineralisation. or changes in rock properties should be included. The area chosen is therefore fairly central to the whole deposit, and forms a small proportion of the whole. The second reason for selecting this sub-area was that both drilling techniques were represented as evenly as possible throughout the area. In this area the deposit has been drilled to about 100 or 120 metres in depth. This gives an adequate amount of detail for the illustration without creating an unwieldy database to work from. The original drilling campaign in this area contained about 80 vertical diamond drill holes. Subsequent infill drilling consisted of some 45 percussion holes distributed over this central study area. The selected area is shown in Figure 1, with the different drilling methods denoted by different symbols. The sample values of only one of the metals has been used in this study.

It can be seen that there is no possibility of comparing the values in a percussion and a diamond drill hole directly. The closest holes are 25 metres apart, and correlation of values between two holes of any type is not sufficiently consistent to allow direct comparisons. Therefore statistical (and geostatistical) methods were used to investigate the relationship between the diamond drilling and the percussion drilling within this area.

Summary statistics

Frequency diagrams (histograms) were plotted of the mineral values of the core sections, separately for the two methods of drilling. These histograms have been plotted on a log-grade scale for greater clarity and are shown in Figure 2(a) and 2(b). Table I shows the number of core sections which have contributed to each histogram, and the arithmetic mean and standard deviation of these sets of data. From the table, it can be seen that the percussion holes average about 35% lower than the diamond drilling results. The percussion cores are also (apparently) less variable than the diamond drilling. This behaviour is also borne out by the histograms in Figure 2. The core sections from the diamond drilling are quite well behaved. given an acceptable fit to a single log-normal distribution under the common statistical tests. The percussion core sections, however, lean much more heavily toward the lower grade end of the histogram. The 'tail' of the histogram into the higher grades is as far extended as that of the diamond drilling - i.e. there are just as high individual grades in the percussion as in the diamond. However, the percussion histogram starts to fall towards the tail at grades less than 1% metal -- whereas the diamond histogram remains high almost as far as 2% metal.

(a) Percussion drilling



(b) Diamond drilling

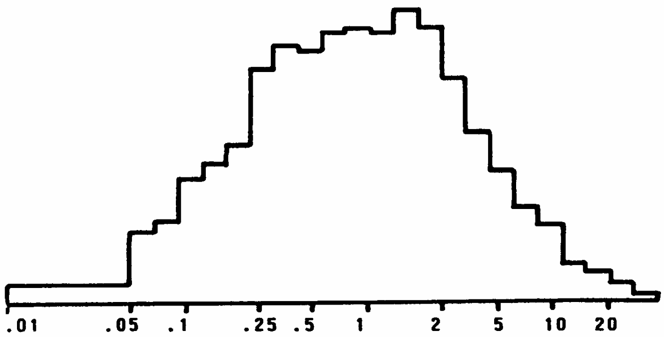


Figure 2: histograms of core section data within study area

Table 1: Summary statistics for metal values in core section data.

statistic	diamond drilling	percussion drilling
number of samples	3045	3399
mean value	2.01	1.34
standard deviation	3.53	2.87

Taking all these features together tends to suggest that there are far more 'low grade' samples amongst the percussion core sections than among the diamond drill cores. There are (at least) three possible explanations for this consistent difference in behaviour between the two drilling techniques:

a. the great variation of lengths amongst the diamond drill care sections may be introducing some sort of bias into an analysis which gives each sample value equal importance;
b. the diamond drill holes may be covering a different geographical area than the percussion holes. That is, the disparity might be caused by percussion holes being sited preferentially in low grade areas;
c. there may be a bias introduced by the sampling technique itself. For example, the percussion drilling method may tend to 'lose' heavy mineral grains down the hole − either to be picked up mixed with later samples or to be lost altogether.

The case study area was selected especially to counter − as far as possible − the second item in the above list. The area is reasonably homogenous. and central to the deposit. No consistent reason can be seen why the percussion holes should give such consistently lower grades than the diamond drilling. Our discussion, then will be confined to possible solutions (a) and (c). Before tackling possibility (a), it was felt that some geostatistical analysis of the original core section data might prove fruitful.

Experimental semi-variograms

Every geostatistical analysis must begin with the calculation of 'experimental' semi-variograms. These graphs reflect the continuity - or lack of continuity - of mineral values within the deposit, or the area under study. The calculation of this graph is based on assumptions of the kind discussed previously. Perhaps it would be worthwhile to repeat them briefly here.

We assume that the mineralisation is a continuous entity. with no sudden barriers or contacts with unmineralised ground. We assume that the relationship between the values at two points within this deposit depends on how far apart they are and possibly on their relative orientation. That is, a pair of samples a certain distance apart (say) vertically above one another will have the same sort of relationship as a pair the same distance apart somewhere else within the same area. Given this assumption, all pairs of samples a given distance apart can be considered as comparable, and can be summarised by a couple of statistics. It is usually assumed at this stage that the 'average difference' between pairs of samples (the same distance apart) is zero. That is, the mineral values do not follow some large scale trend across the deposit or study area. If the 'average difference' is zero, then the 'variance of the differences' reduces to being simply the average squared difference between the values of samples a specified distance apart. The process of calculating this variance is thus fairly simple: select a direction of interest (say vertical or 'down-the-hole'); select a particular distance (say 5m); find a pair of samples this distance apart; calculate the difference between the mineral values and square it; repeat this for all pairs of samples which can be found that distance apart; average the values obtained.

This process will produce a single value for 'variance of the difference in mineral value' or average squared difference. This value will relate to one specified distance. If we plot a graph of the variance of the difference versus distance between samples' we obtain a variogram. The basic tool of geostatistics is the semi-variogram, or half this variance plotted against the distance between the samples. Each selected distance (in a particular direction) will give one point on a semi-variogram. Building up a complete graph using many distances provides us with a 'picture' of how the relationship between sample values varies with the distance between them.

The Case Study

Let us return, then, to the area under study. For this illustration we have chosen to calculate 'down-the-hole' semi variograms, only. This is the most stable direction at this stage of exploration, since it is the direction which has been most densely sampled. The closest drill holes are 25 metres apart. The closest core sections are one metre apart down the hole. vertically through the deposit. 'Vertical' semi-variograms were calculated for percussion holes and diamond drill holes separately. These are shown in Figure 3.

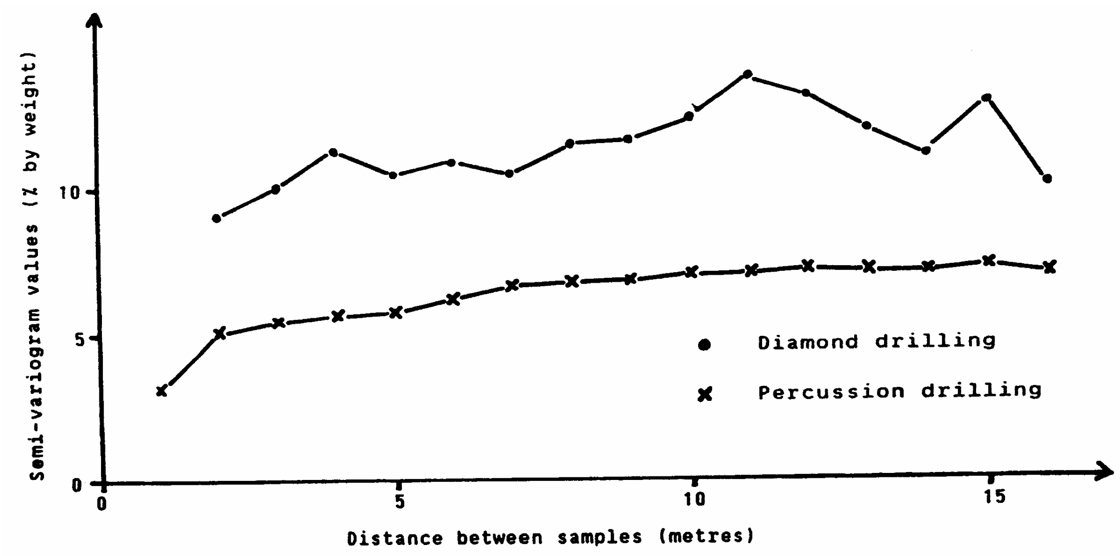


Figure 3: Experimental semi-variograms from metal values in core sections.

The line produced by the diamond drilling appears to be far more erratic and almost twice the height of the percussion drilling results. The percussion semi-variogram also looks somewhat smoother than the diamond drilling, although with so little structure it is difficult to say whether this is significant.

It has been seen from the histogram figures that the mineral values tend to follow a (more or less) log-normal type of behaviour. It is well. known[3] that the height of the semi-variogram is proportional to the ordinary statistical variance of the sample values. It is also well known that the variance of sub-samples from a log-normal population tend to be proportional to the square of the sample mean. Therefore, the difference in height between these two curves may be simply a reflection of the sample log-normality, rather than a difference in geological structure.

It is fairly simple to check this property. If the mineral values follow a log-normal distribution, the logarithms of those values should follow a Normal distribution. This is the reason the histograms in Figure 2 were plotted on a log scale. Logarithms were taken of the mineral value within each core section, and semi-variograms constructed on these values. The experimental semi-variograms are shown in Figure 4.

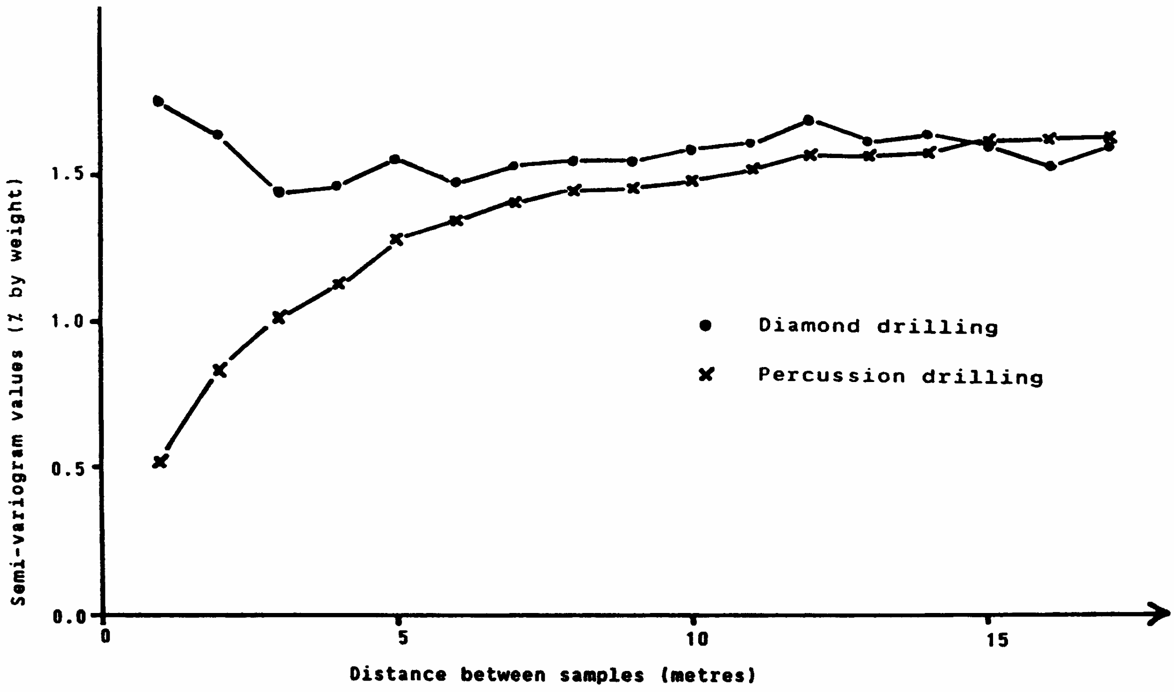


Figure 4: Experimental semi-variograms from logarithms of metal values in core sections.

These 'logarithmic' semi-variograms should show the same sort of structure (shape) as the 'grade' semi-variograms would have, except that the estimation will be more stable and the . 'proportional effect' should be absent. Visual comparison of the two semi-variograms for percussion drilling and diamond drilling reveals that the two are obviously different. They both tend toward the same level or sill, suggesting that the global variability within the two types of drilling is comparable. However, the percussion core sections show a stable slow rise towards this sill, indicating a high degree of continuity in the mineral values between samples up to about 5 or 6 metres apart. The diamond drilling, on the other hand, seems to suggest that neighbouring samples tend to be more different than samples 3 or 4 metres apart. This would 2suggest a bedded structure, with beds 2 or 3 metres thick. Taken in conjunction with the geological model developed previously, it would seem that the interpretation of the diamond drilling semi-variogram is quite reasonable.

The calculation of the semi-variograms would seem, therefore, to support alternative (c) in our set of explanations in the previous section. However, it is still possible that the differences in both histograms and semi-variograms could be occasioned by the disparity in core section length within the diamond drill holes. Alternative (a) cannot be ruled out until this problem is tackled.

Bench compositing

The disparity between diamond drilling results and percussion drilling results may be due to the fact that, whilst the percussion holes were sectioned almost exclusively at one metre intervals, the diamond drill cores vary from 40 cm to 4 metres in length. To produce two comparable sets of data, it is necessary to composite core sections into constant lengths for both types of drilling separately. There are two ways to composite:

1. start at the top of a hole and combine the next 5m (say), then the next 5m and so on;
2. define fixed benches within the area and combine all core sections in a hole which lie within that bench.

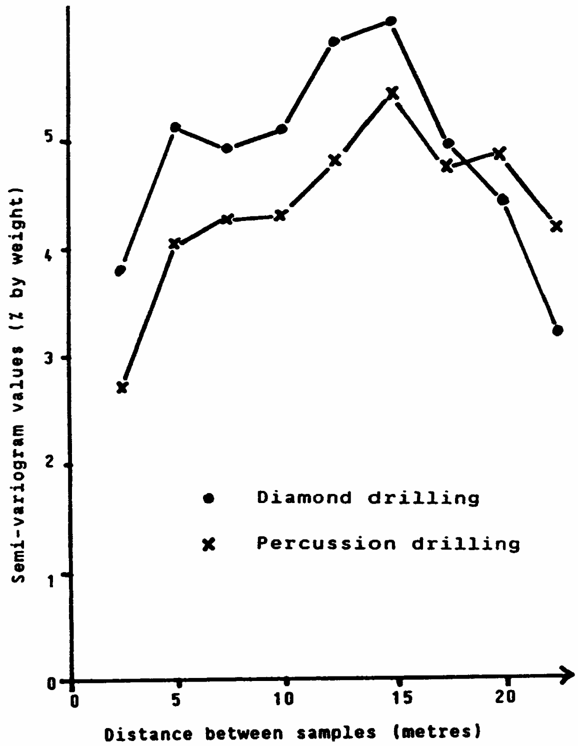
The second of these methods was chosen for this study.

The percussion core section data were composited into 5 metre 'bench' composites. This bench height is chosen as being that relevant to the expected mining bench height. Also, given the structure of the percussion core section semi-variogram, a larger composite would wipe out any structure which was present. A smaller composite would not provide the consistent set of core composites which we are trying to create from the diamond drilling. The diamond drilling was composited on the same set of 5 metre benches. Semi-variograms were calculated on the grades of these composite cores, for the two types of drilling separately. These are shown in Figure 5. Apart from a slight difference in height between these curves - which might be a hangover from the proportional effect - the two look very similar indeed. That is. 5 metre composites from the two types of drilling give the same type of continuity down the hole. This would appear to give strong support to alternative (a), that the disparate cores on the diamond drilling were introducing a supposed 'bias' into the sample values and, incidentally, overvaluing the reserves by some 33%.

As an independent check on this conclusion, summary statistics and histograms were also produced on this composite data. Since the core sections are more consistent in 'support' than before, the diamond drill composites should produce a more realistic shape to the histogram – and a more realistic estimate of the average grade of the deposit. The summary statistics are shown in Table 2 and the histograms in Figure 6.

The average grades as calculated from each type of drilling have both been reduced. However, the percussion average is 68t of the drilling average -- as calculated from these new consistent 5 metre composites. That is the percussion holes still appear to contain 32% less metal than the diamond drill holes. The standard deviations are much closer than before, as would be expected, and bear out the comparable nature of the semi-variograms. We are left, then, to conclude that the continuity structure of 5 metre composites is similar in both the two types of hole -- but that the contained metal reflected by the percussion results is considerably lower than that apparently measured in the diamond drill core sections.

Figure 5: Experimental semi-variograms from 5m composites of metal values.



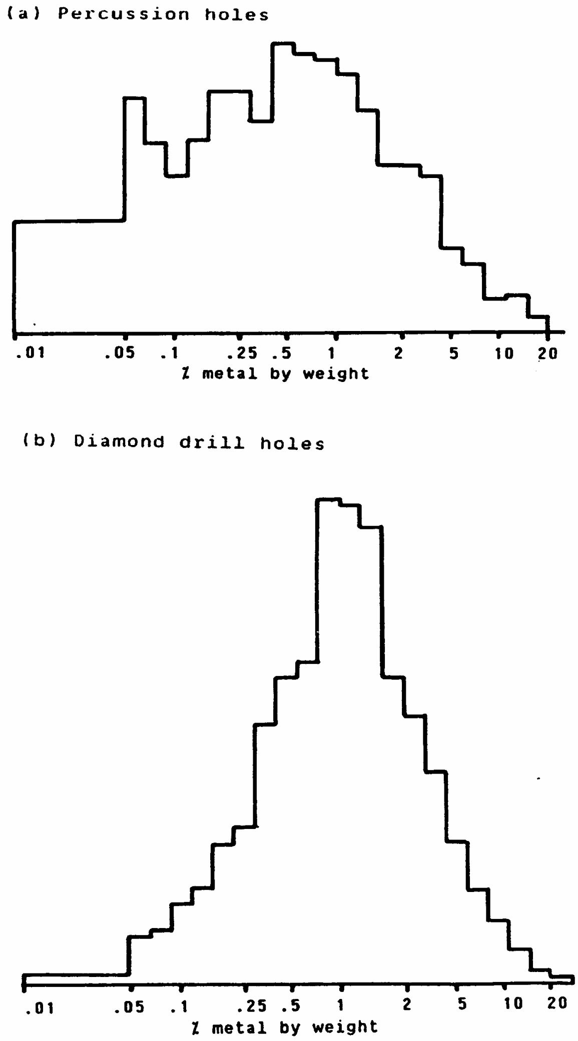


Figure 6: Histograms of 5m composited metal values within study area.

Table 2: Summary statistics for composited metal values in drill cores.

statistic	diamond drilling	percussion drilling
number of samples	1138	778
mean value	1.75	1.19
standard deviation	2.27	2.17

SUMMARY

The considerations which affect the estimation of block averages prior to a pit planning exercise fall into two stages;
A geological, statistical and/or geostatistical modelling process to determine the 'best' method to use in the estimation of individual block values;
The implementation of the chosen estimation method, generally nowadays using a computer and possibly a general computer package.

This paper has confined itself to a discussion of the first of these two stages, since the second is amply covered in the literature and various sales brochures. Several problems have been mentioned which might occur during the modelling stage, and one of these has been discussed in great detail in the guise of a case study.

The conclusion which must be drawn from this case study is that in this particular case the two drilling methods employed within the deposit do not produce comparable results. No argument has been put forward as to which method is the more reliable indicator of 'metal in the ground', although it is difficult to imagine what sampling method could overestimate the contained metal to the tune of over 30%. It seems much more likely that the percussion technique in this case was leaving mineral grains at the bottom of the hole. The reader has probably also noted that the author puts forward no solution to this problem. This is completely intentional.

The argument which the author wishes to advance in this paper, and to illustrate by this case study, is that the 'modeller' (geologist, planning engineer or whatever) must put himself firmly into the driving seat -- even if he has little prior idea of the best route to his final destination, which is the best ore reserve estimate for his deposit.

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