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A GEOSTATISTICAL APPROACH TO COAL RESERVE CLASSIFICATION

by

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ABSTRACT

There is an increasing need for reliable and comparable coal resource data and it is necessary to standardize the traditional classification procedures by quantifying the three basic evaluation criteria of economic feasibility, geologic assurance and recovery. For well documented deposits, geostatistical methods can considerably improve classification quality.

A geostatistically based algorithm for classifiying coal resources within the current Queensland and New South Wales codes has been developed. Application of the method in classifying resources from a number of seams exhibiting different structural characteristics is assessed. The method is found to give classification results which closely reflect the error associated with an estimate of resource quantities based on current sampling densities. It requires a careful geostatistical analysis with emphasis on geological awareness. Resource category restrictions must be arbitrarily assigned and remain constant for all deposits being compared. Engineering judgement is needed and interpretation may be required with isolated and peripheral blocks.

INTRODUCTION

The economic incentive to assess and classify mineable coal resources so as to enable the calculation of reserve tonnage and grade has increased significantly with present commodity marketing conditions. Improvements to classification concepts and definitions are needed as it is recognized that no current practices produce results which are free of some degree of subjectivity and therefore readily reproducable. Quantification of geological assurance is a major difficulty in most classification codes. The magnitude of the error associated with an estimate of the quantity and quality of a resource needs to be understood. Geostatistics allow calculation of the variance of errors associated with an estimate and is a potentially valuable tool for classifying resources on the basis of geological assurance.

A geostatistically based algorithm for classifying coal resources within the framework of the current Queensland and New South Wales codes has been developed. The method is described and its application in classifying resources from a number of seams exhibiting different structural characteristics is assessed.

QUEENSLAND AND NEW SOUTH WALES COAL CLASSIFICATION CODES

A major requirement for any new classification procedure is that relevant statutory requirements for establishing resource classes needs to be recognized. Galligan and Mengel (1986) describe the current Queensland and New South Wales codes. Features of these which are relevant to a geostatistical approach include the following:

(1) Points of Observation.

A point of Observation is an intersection at a known location, of coal bearing strata, which provides information about the strata by one or more of the following methods:

• Observation, measurement and testing of surface or underground exposures.

• Observation, measurement and testing of borecore.

• Observation and testing of cuttings, and use of downhole geophysical logs of non-cored boreholes.

A point of observation for coal quantity may not be used necessarily for coal quality. The most reliable quality information is provided by testing of surface or underground exposures or by testing of borecore.

Geophysical techniques such as seismic surveys are not direct points of observation.

(2) Coal Resources.

Coal Resources are all of the potentially usable coal in a defined area, and are based on points of observation and extrapolations from those points.

(3) Categories of Resources.

(a) Measured Resources.

The points of observation generally should not be more than 1 km apart. Where geological conditions are favourable it may be possible to extrapolate known trends a maximum distance of 0.5 km from points of observation.

(b) Indicated Resources.

Points of Observation generally should be not more than 2 km apart. Where geological conditions are favourable, it may be possible to extrapolate known trends a maximum distance of 1 km from points of observation.

(c) Inferred Class 1 Resources.

Points of Observation generally should be not more than 4 km apart. Extrapolations of trends should extend not more than 2 km from points of observation.

THE GEOSTATISTICAL APPROACH TO CLASSIFICATION

SCOPE AND APPLICABILITY OF GEOSTATISTICS

The use of geostatistics requires quantitative data and certain minimum restrictions with respect to the number and positions of

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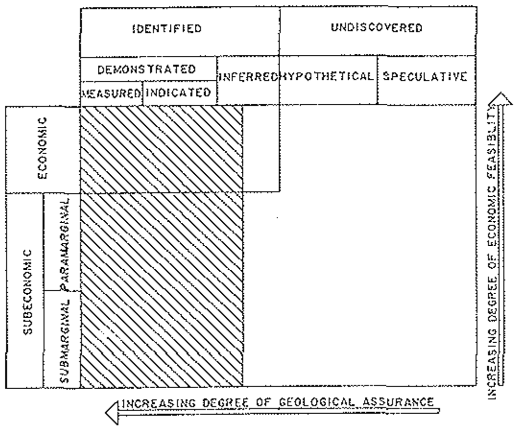

Figure 1: McKelvy box scheme (as recommended by the USBM/USGS) the hatched area represents that portion to which geostatistical methods may be applicable.

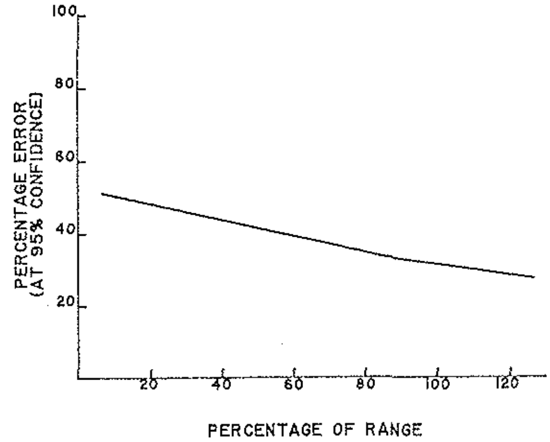

Figure 2: Relative kriging error (at 95% Confidence Level) versus block side dimension as a percentage of variogram range.

sample information. Theoretical reasoning and practical experience have shown that a minimum of 30 to 50 sample points evenly distributed over any field of interest are necessary to obtain a reliable variogram. Hence a resource classification system based on geostatistics must be restricted to fairly well documented deposits. As a rule of thumb Deihl and David (1982) suggest that geostatistical methods are only applicable to those resource classification categories covered in the hatched area of the McKelvy box (Fig.1). This roughly equates to the measured, indicated and inferred class 1 categories of the new Queensland Code.

THE INFLUENCE OF BLOCK SIZE ON CLASSIFICATION

The estimation variance σ_k^2 of any deposit parameter is a function of the size of the block being estimated as discussed by Deihl and David (1982). Any block classification which is dependent on estimation variance is therefore a function of block size. As an example, using a set of borehole data for an irregularly drilled brown coal deposit, the relative error of estimation has been calculated at a 95% confidence limit (equation 1) for square blocks of varying sizes. The results of these calculations are shown in Figure 2 and indicate the influence of block size on kriging variance and hence on the outcome of resource classification. The percentage error calculated by equation 1 has been plotted against the length of the block sides expressed as a percentage of seam thickness variogram range.

$$R = \frac{1.96\ \sigma_k}{Z^*} \qquad (1)$$

Where R = relative error at a 95% confidence level,

σ_k^2 = estimation variance (Kriging variance) and

Z^* = estimated value of the parameter

From a statistical point of view it is clear that classification of resources without considering the relation between the respective deposit quantity and the estimation variance is meaningless. The solution to this problem is neither simple nor straightforward and in fact Sabourin (1983) noted that there are almost as many proposed solutions as there are authors who have considered the problem. It is beyond the scope of this paper to review all proposed solutions, although it is worth noting, that in many cases interim solutions only are suggested, such as in the German Gesselschaft Deutsher Metallhuton und Bergluete system (Wellmer, 1983).

The following reasoning leads to a definition of maximum block size which combines some of the better aspects of a number of the solutions proposed by different authors, while observing the restrictions inherent in the current Queensland and New South Wales codes.

It has been common practice for resources to be estimated using blocks which have a side dimension related to the drill hole spacing (Figure 3). In this case the maximum block size allowable for each class of resource is therefore dependent on the maximum drill hole spacing for that class. This limit on block size is therefore suggested for use in the proposed geostatistical solution.

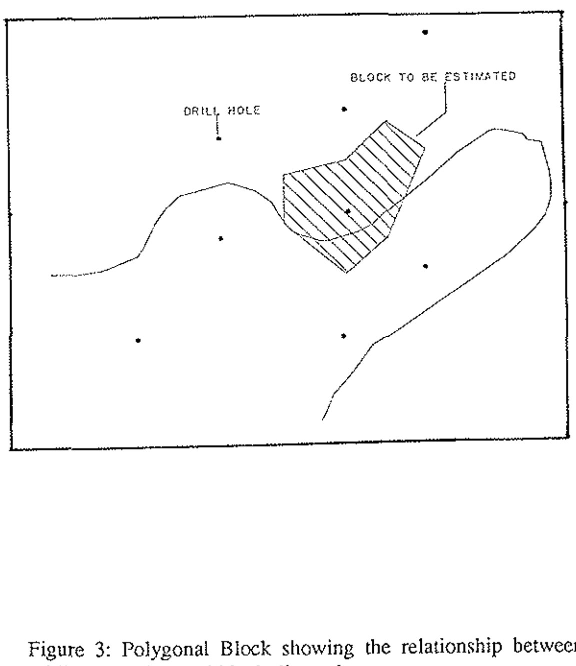

Figure 3: Polygonal Block showing the relationship between drillhole spacing and block dimensions.

CLASSIFICATION CLASS CRITERIA

A resource class system has been defined for use in the study. Important features are that maximum drill hole spacing for each class are based on those specified in the current Queensland code and maximum allowable error for class A resources are based on the estimation error specified for the most restrictive resource class (measured) uder the Queensland Coal Reserve code in use up to 1985. Error limits for the less restrictive classes B and C have been assigned arbitrarily although they follow recommendations put forward by Fettweis (1979), Diehl and David (1982) and Wellmer (1983). this information is summarized in Table 1.

Resource Class	Maximum allowable error % (95% C.L.)	Maximum drillable spacing km	Maximum block area km^2
A	20	1	1(=1^2)
B	40	2	4(=2^2)
C	60	4	16(=4^2)

Table 1: Preliminary resource classification criteria. Drill hole spacing based on Queensland and New South Wales Codes.

The proposed algorithm is an iterative method which starts with a small block which is enlarged step by step. After each increase, the area of the enlarged block and associated kriging variance are calculated and compared with constraints for the first and most restrictive resource class. If both area and confidence interval calculated from the kriging variance (σ_k^2) satisfy the constraints the block is classified to this restrictive category, class A. Should the area of the block under study surpass the upper limit of class A without obtaining the necessary precision, the procedure continues with the less restrictive requirements of class B and so on until the block is finally classified. In order to maximise the resource quantities in the upper classes, the iteration procedure begins at the location with the lowest value for σ_k^2 determined by point kriging the deposit on a regular grid. Subsequent stepwise extensions of any block are constrained by the principle that an increase is always performed in the direction where the gradient of precision or rate of change of σ_k^2 is least. After final classification, the block area is recorded on file, the results of the estimation printed and the procedure re-starts at another point with local minimum kriging variance.

A FORTRAN program has been written to perform the classification automatically for one selected parameter. A series of checks within this program ensure that the shape of the developing block is controlled to avoid intricate block contours.

STEPS IN IMPLEMENTING A GEOSTATISTICALLY BASED RESOURCE CLASSIFICATION SYSTEM

Deihl and David (1982) defined the following steps for a geostatistical classification of resources:

1. Determination of relevant parameters such as coal thickness or ash content.
2. Review of raw data and preparation of basic data files.
3. Classical statistical analysis of parameter data and variogram calculation.
4. Determination of the outline of presently feasible resources by geological and technical criteria.
5. Further sub-division of the areas defined in point 4. into blocks which satisfy the predefined constraints of a specific category of geological assurance with respect to:
   (a) dimensions, and
   (b) parameter confidence levels
6. Calculation of in-situ and recoverable tonnages of each block defined in point 5 and compilation of total quantities for each class of resource.

The above steps are standard well-defined procedures in practical geostatistics with the exception of point 5 which required the development of a special algorithm.

The division of a coal deposit into zones satisfying the criteria of different classes of resource presents fundamental problems. Defined blocks need to satisfy these constraints in respect of both area and the precision of the grade estimates. Any adopted algorithm should guarantee that a maximum resource tonnage is assigned with the highest degree of geological assurance sequentially to the first category and from the remaining quantity to the second category and so on.

APPLICATION OF THE GEOSTATISTICALLY BASED CLASSIFICATION METHOD

CASE STUDY 1 - CLASSIFICATION OF A LATERALLY PERSISTENT DEPOSIT

An undeveloped brown coal deposit was analysed according to the previously mentioned procedures using the limits for various classes of resource detailed in Table 1. The deposit was sampled an an irregular grid by 91 drill holes extending over a region 7.5 km north-south by 3.5 km east-west. Three major coal plies were identified. Classification results for the lowest ply only are discussed.

Figures 4(a) and 4(b) show the locations of exploratory drill holes; the circles represent arbitrary ranges of influence for each hole. Using this type of arbitrary assignment it can be seen that areas of a deposit can be placed in a number of different classes of resource depending on the range of influence selected. This highlights the need for an objective method for classifying resources.

Preliminary statistical analysis of the seam thickness data suggested a bimodal distribution, and several apparently anomalous data points were also indicated. Analysis of the seam thickness contours (Figure 5), indicates that no valid reason exists, based on current information, for excluding any of the data points and all further analysis is therefore based on the complete data set.

A large number of attempts were made to calculate an experimental variogram model which accurately described the ply's thickness. The final theoretical variogram which has been used follows an isotropic spherical model with a range of 2300 m, a sill of 0.29 m^2 and no nugget effect (Fig.6). Although the geology of the deposit indicated possible anisotropy insufficient data existed for this step to be undertaken.

Validation of the variogram model by a "jack-knifing" method indicates that it provides an accurate description of the ply thickness over the field of interest.

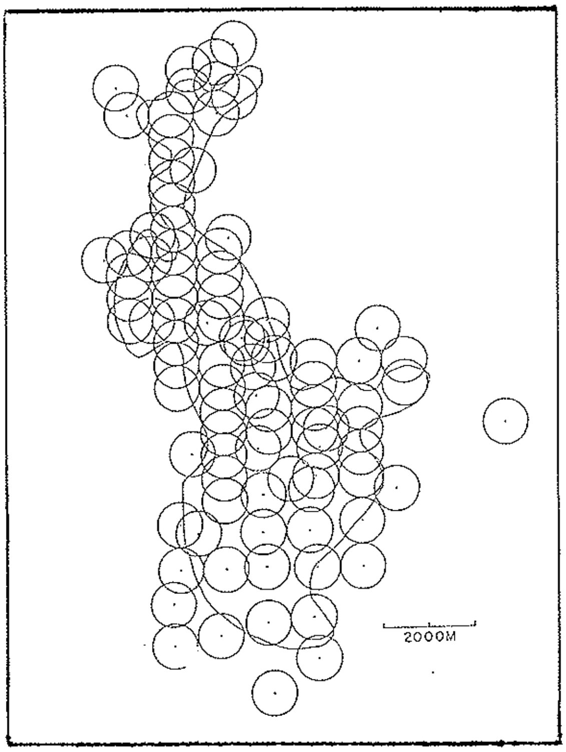

Figure 4(a): Exploratory drillhole locations for Case Study 1 showing 500m ranges of influence.

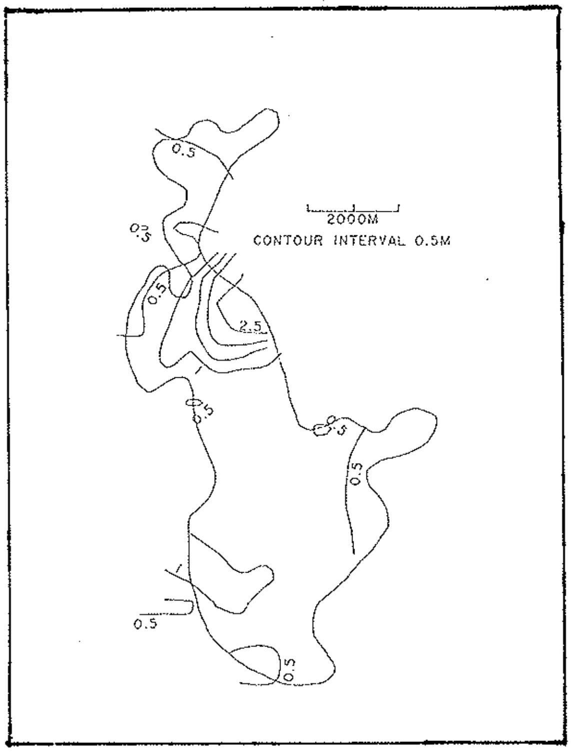

Figure 5: Seam thickness contours - Case Study 1.

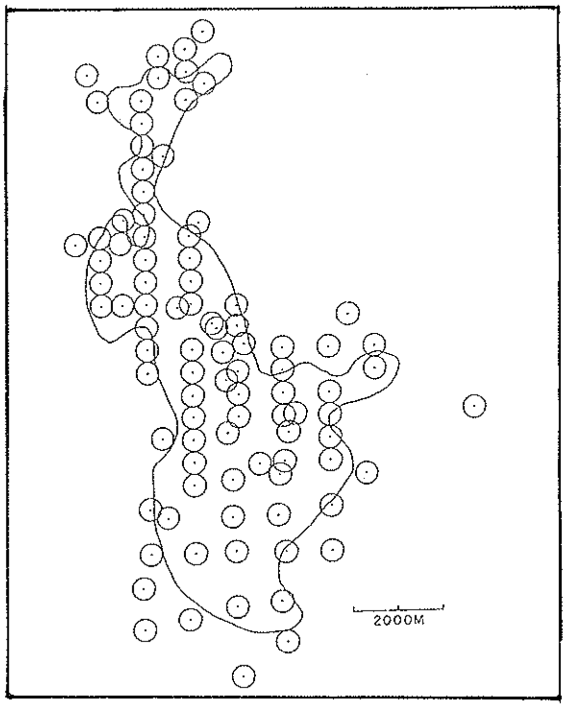

Figure 4(b): Exploratory drillhole locations for Case Study 1 showing 250m ranges of influence.

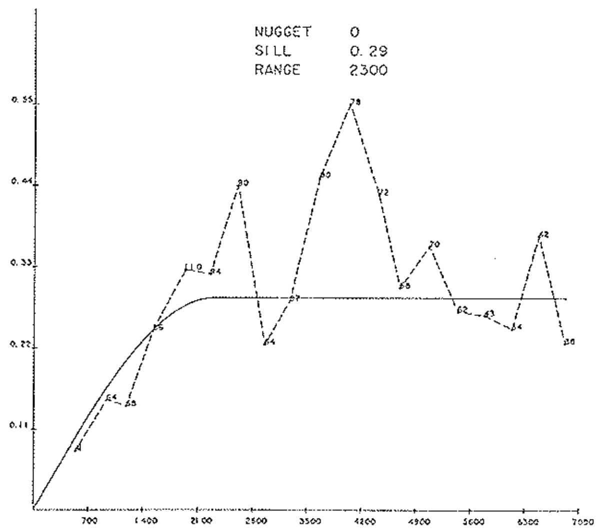

Figure 6: Average variogram for seam thickness - Case Study 1.

The deposit was kriged with 500 m by 500 m blocks and the resulting thickness and estimation errors (at a 95% confidence level) contoured (Figures 7 and 8). At first examination, the contours of estimation errors indicate that the possibility of any significant resources falling in the measured category is slight.

Classification of the deposit was carried out using the geostatistically based computer program using square block iterations with a side dimension of 500 m. The results have been plotted and are presented in Figure 9 and Table 2. The majority of the regions assigned to the various classes closely follows the distribution which would be expected from contours of relative error (Figure 8).

As expected only a very small region has been classified as A class, a total of 2.5 square kilometers from a deposit covering some 31.5 square kilometers. What is at first glance surprising is that the A class region does not correspond to the area of highest drilling density. This may be easily explained by the fact that the classification is based on relative precision (error/estimate) rather than error alone. For this reason the class of resource to which a particular region is assigned is a function of both the drilling density and the seam thickness in that region.

A number of regions near the deposit boundary remain unclassified. This situation occurs due to the constraints placed on the growth of these regions by previously classified regions and the deposit boundary. It should be noted, however, that the deposit boundary tends to be a region of high uncertainty. This is reflected by the fact that, with few exceptions, regions near the boundary are classified into the least restrictive classes of resource. For this deposit, and with knowledge of the existence of coal seam continuity, it is recommended that unclassified areas which fall within the deposit boundary be considered as falling within the lowest restrictive class of resource.

Another apparent anomaly is the existence of two isolated C class regions (blocks 18 and 21, Figure 9), surrounded by B class regions. The presence of these regions may be attributed to the restrictions placed on their growth by previously classified regions and the fact that they represent isolated zones of high estimation error. Such locations exist due to isolated thinning of the deposit or a local decrease in drilling density. Whatever the reason for the existence of a particular isolated region it is clear that each should be given close individual attention at the final stage in the classification process. Some subjective judgement is at present considered unavoidable in the treatment of such regions leading to the conclusion that

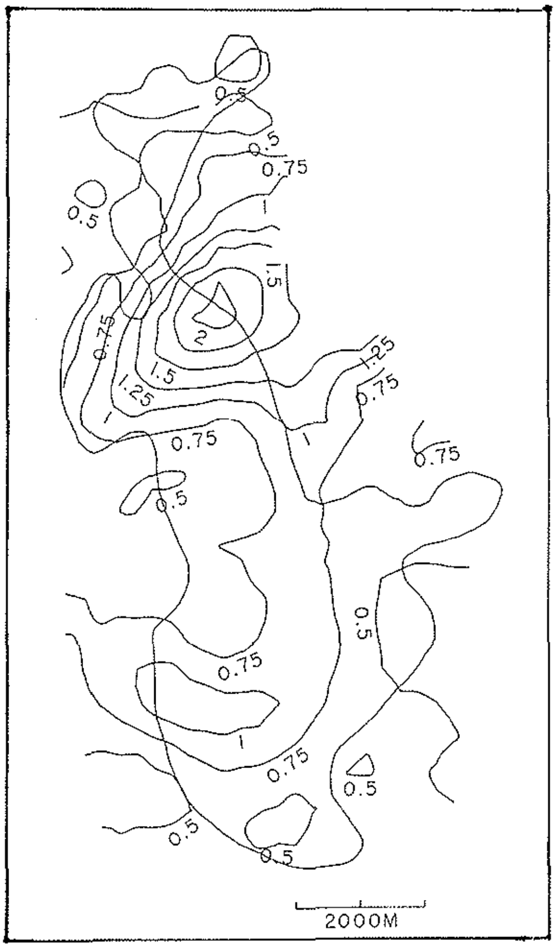

Figure 7: Kriged seam thickness contours based on 500m x 500m blocks - Case Study 1.

A class				B class				C class				U class			
Blk	TK	Area	Vol.	Blk	TK	Area	Vol.	Blk	TK	Area	Vol.	Blk	TK	Area	Vol.
1	1.316	0.25	0.329	2	0.67	1.25	0.84	10	0.65	2.5	1.61	19	0.47	1.25	0.591
7	0.811	1.00	0.811	3	0.65	1.25	0.81	18	0.59	0.5	0.30	28	0.68	0.75	0.513
8	2.371	0.25	0.593	4	0.66	1.25	0.86	20	0.62	0.75	0.46	29	0.43	0.25	0.107
11	2.960	0.25	0.740	5	0.99	1.25	1.27	21	0.65	0.25	0.16	30	0.59	2.00	1.184
12	1.527	0.50	0.764	6	0.64	2.25	1.43	25	0.75	0.50	0.38	32	0.44	0.25	0.109
14	2.486	0.25	0.622	9	0.69	1.25	0.87	26	0.88	0.50	0.44	33	0.57	0.25	0.142
				13	0.71	1.25	0.88	27	0.92	0.25	0.23				
				15	0.65	3.00	1.95								
				16	0.61	1.25	0.77								
				17	1.09	1.25	1.37								
				22	1.15	2.75	3.17								
				23	1.14	0.50	0.57								
				24	1.67	0.25	0.42								
				31	2.69	0.25	0.67								
Total			3.86				15.9				3.6				2.6

Table 2: Preliminary classification results for case study 1.

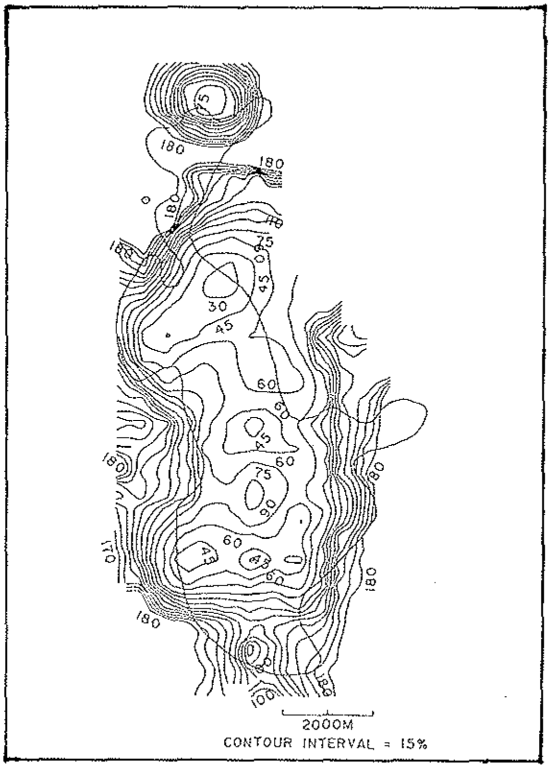

Figure 8: Relative kriging error (95% confidence level) contours based on 500m x 500m blocks - Case Study 1.

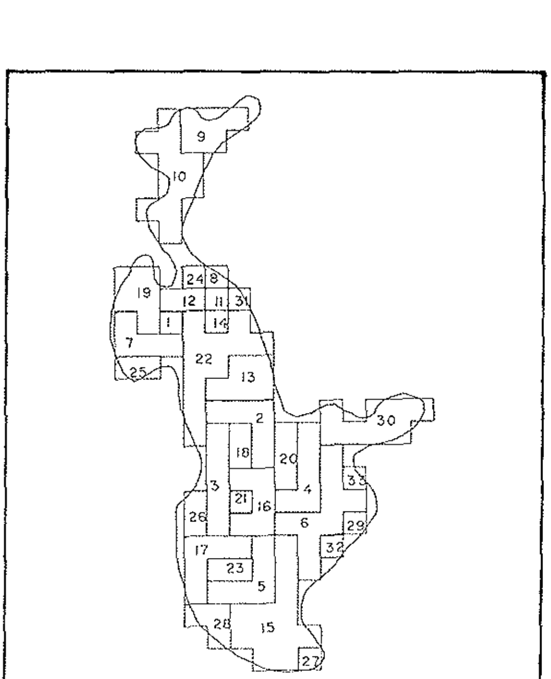

Figure 9: Resource classification results - Case Study 1.

further work is needed to address this problem. For the purpose of this case study these isolated regions were considered to be of sufficient size to be classed as independent of the surrounding blocks and to therefore accurately represent the presence of locations of low relative precision. The two regions under question, blocks 18 and 21, were consequently left unchanged from the original computer based classifications. Final results for this deposit are presented in Table 3.

CASE STUDY 2 - CLASSIFICATION OF A STRUCTURALLY DISTURBED DEPOSIT

An anthracitic deposit was chosen as the second case study because of the highly structurally-disturbed state of the seams. Complex faulting in this area gives rise to several fundamental problems not evident in the analysis of the brown coal deposit. Major structural features of this anthracite deposit and locations of drill holes are shown in Figure 10.

Preliminary investigations of the sample information indicated the need to sub-divide the deposit into regions which were accepted as geologically continuous for the purposes of geostatistical analysis. Two major regions were identified, the area north of fault A (Figure 10) and the larger area to the south. The southern zone is of greater interest and will be discussed. Classical statistical analysis of the raw sample data revealed a standard deviation of almost 50% of the sample mean of about 4.1 m thickness. The large value of the standard deviation can be attributed to the presence of a number of apparently anomalous high thickness values.

In particular it is noted that three samples recorded thicknesses greater than 13.0 m. Removal of all data lying in oxidised regions did little to improve the results.

Contouring of raw thickness values, however, revealed the presence of a large number of isolated high and low values (Figure 11(a)). This situation is clearly illustrated in Figure 11(b) in which adjacent sample values range from 7 m to 2 m. Further investigations showed that these were a reflection of the high degree of structural disturbances present in the region. Systems of normal and reverse faults effectively isolate small blocks of the region into areas which should be analysed separately (Figures 12(a) and (b)). These geological characteristics make it extremely difficult to apply geostatistics, or indeed any estimation method to this region. Consequently this is considered to be an area where geostatistical classification is difficult to apply.

Various attempts were made to construct a variogram model for this region. The experimental variogram exhibited a spherical model structure with a short range hole effect. The hole effect is a reflection of the closely spaced seam structural changes and so distorts any analysis based on an examination of seam thickness. This emphasises the fact that any geostatistical analysis undertaken without due emphasis to deposit geology may be misleading and result in highly erroneous conclusions.

CONCLUSIONS

Coal resource classification concepts and definitions have been studied and a geostatistically based algorithm derived for assigning base blocks to classes of varying geological assurance. In use, the algorithm gives classification results which closely reflect the error associated with the kriged estimate of resource quantities.

A class				B class				C class			
Blk	TK	Area	Vol.	Blk	TK	Area	Vol.	Blk	TK	Area	Vol.
1	1.316	0.25	0.329	2	0.67	1.25	0.84	10	0.65	2.5	1.61
7	0.811	1.00	0.811	3	0.65	1.25	0.81	18	0.59	0.5	0.30
8	2.371	0.25	0.593	4	0.66	1.25	0.86	20	0.62	0.75	0.46
11	2.960	0.25	0.740	5	0.99	1.25	1.27	21	0.65	0.25	0.16
12	1.527	0.50	0.764	6	0.64	2.25	1.43	25	0.75	0.50	0.38
14	2.486	0.25	0.622	9	0.69	1.25	0.87	26	0.88	0.50	0.44
				13	0.71	1.25	0.88	27	0.92	0.25	0.23
				15	0.65	3.00	1.95	19	0.47	1.25	0.591
				16	0.61	1.25	0.77	28	0.68	0.75	0.513
				17	1.09	1.25	1.37	29	0.43	0.25	0.107
				22	1.15	2.75	3.17	30	0.59	2.00	1.184
				23	1.14	0.50	0.57	32	0.44	0.25	0.109
				24	1.67	0.25	0.42	33	0.57	0.25	0.142
				31	2.69	0.25	0.67				
Total			3.859				15.88				6.23

Table 3: Final classification results for case study 1.

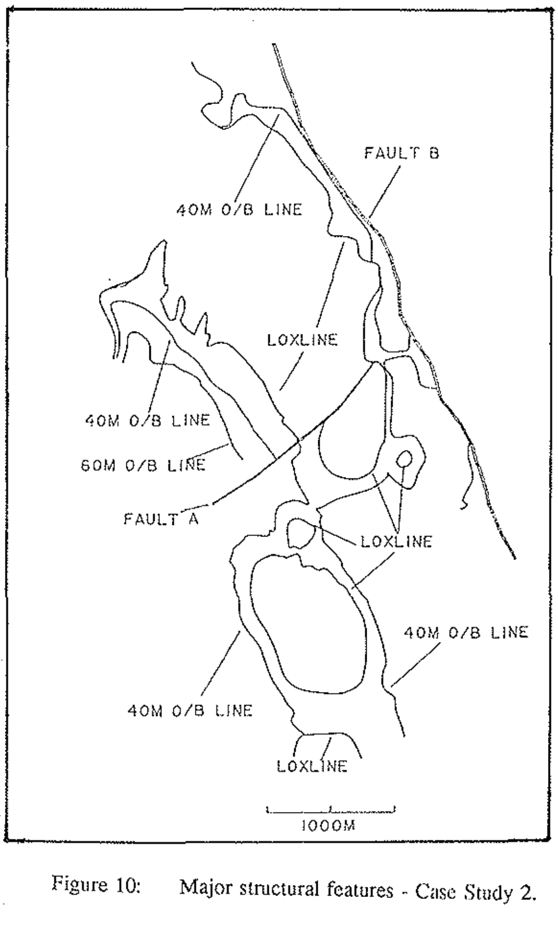

Figure 10: Major structural features - Case Study 2.

The method provides a consistent basis for comparison of different deposits. It requires a careful geostatistical analysis with particular emphasis on details of geological variations. From its use, it is possible to predict the increase in sampling density required to attain a higher classification category for a particular area. Results are readily reproducable and require a minimum of subjective judgement. Resource category restrictions must be arbitrarily assigned and remain constant for all deposits being compared.

Finally, it must be emphasised that, as with all classification approaches, engineering judgement is needed. In particular, interpretation may be required with isolated and peripheral blocks. Further research is warranted on these aspects.

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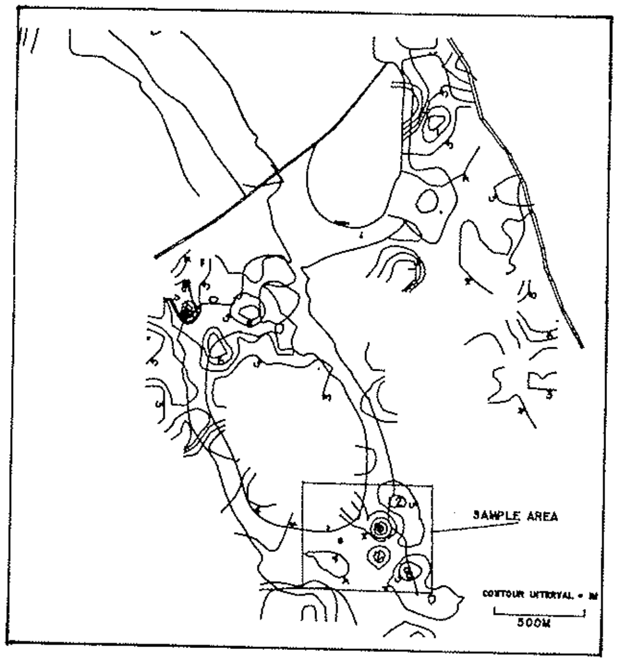

Figure 12(a): Structural features of the southern region of Case Study 2.

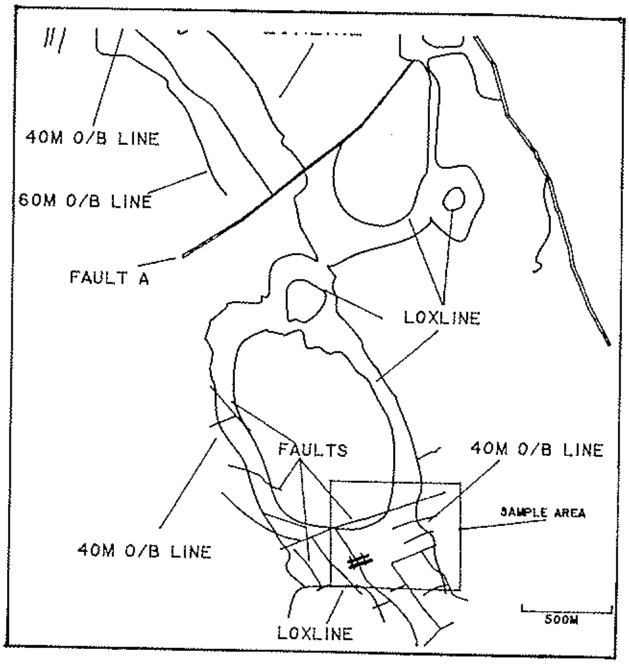

Figure 11(a): Seam thickness contours for the southern region of Case Study 2.

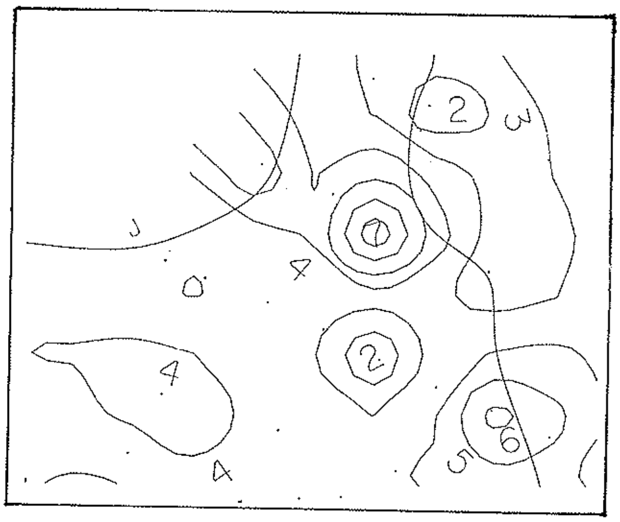

Figure 11(b): Expanded view at the sample area shown in figure 11(a).

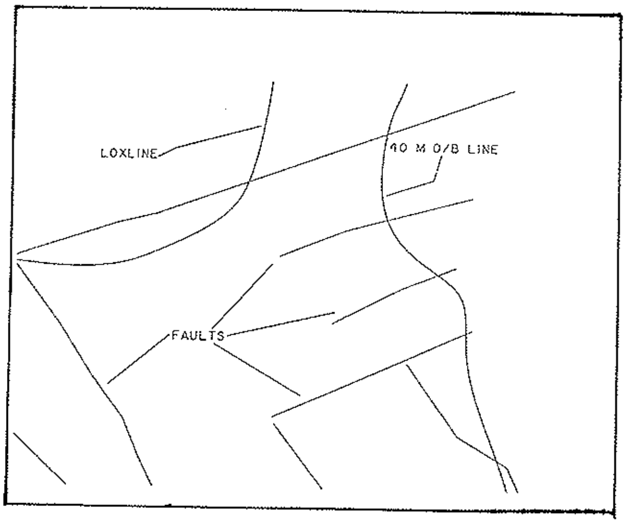

Figure 12(b): Expanded view of the sample area shown in figure 12(a).