bulk solids handling Volume 1 Number 3, September 1981

Introducing Geostatistics to the China Clay Industry

Andrew R. Camp, England

Die Einführung der Geostatistik bei der Kaolingewinnung
Introduction de la géostatistique à l'industrie du kaolin
Introduciendo geoestadística a la industria del caolín
チャイナクレー産業への地質統計学の導入
瓷土工业的刚体力学介绍
تقديم الاحصاءات الجيولوجية الى صناعات الفخار في الصين. بقلم ايه. آر. كامب.

Summary

E.C.C. Ltd. extracts clay matrix from primary kaolin sources in the South West of England, the properties of which are inherently variable. Quality control procedures during the stages of processing ensure that the final products meet market requirements. Borehole samples are used to assess the geometry and overall properties of the deposits for planning pit development.

In a changing market involving the use of advanced technology, new methods of quality control are continually being investigated. This paper discusses a series of experiments which have been carried out to examine the use of mathematical and statistical methods as applied to borehole information with the object of supplementing existing knowledge of the variations within the deposit. These experiments have subsequently resulted in the widespread use of geostatistics within the Company.

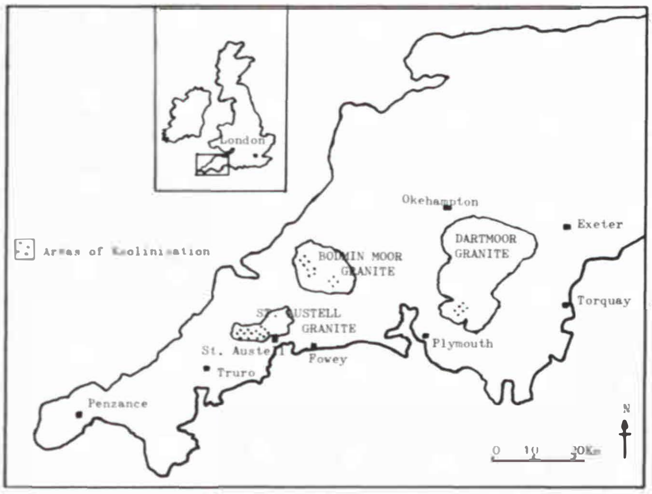

Fig. 1: China clay deposits of S.W. England

1. Description of the Clay Industry

1.1 The Company and its Markets

English China Clays Ltd. (E.C.C.) is the largest producer of china clay in the United Kingdom. The industry is concentrated in the St. Austell area of Cornwall and there are also operating plants on Bodmin Moor and on Lee Moor in Devon (Fig. 1). E.C.C. also have operating companies in North and South America, Europe, Japan and Australia and its deposits are not confined solely to china clay. For example, E.C.C. Ball Clays Ltd., which operates in Devon and Dorset are one of the most important producers of ball clay in Europe.

The traditional market for china clay is the ceramic industry where it is used in the production of bone china, earthenware, sanitaryware, tiles and refractories but as Table 1 shows this represents a relatively small percentage of total sales.

Table 1: Uses of China Clay

	% of Total Sales Volume
Paper	80
Ceramics	15
Other uses	5
	100

The bulk of the material is sold to the paper industry either as a filler, where it is used to fill the interstices of the pulp fibres or as a surface coating, to produce a smooth, bright and usually glossy finish. Other industries using china clay include paint, rubber, plastics, pharmaceuticals, insecticides and fertilisers where the clay is used as an anti-caking agent.

In all, E.C.C. produces approximately 30 different clay products, each one having its own quality specification such as particle size distribution, brightness, viscosity and chemistry: some ceramic clays can have over 10 separate quality specifications which must be adhered to.

Andrew R. Camp, Digital Equipment Co. Ltd.,
Digital Park, Worton Grange, Reading, Berks., England

1.2 Geology, Extraction and Processing

China Clay (Kaolin) was formed *in situ* by the decomposition of the feldspars in the granite. However, the extent of the decomposition was not complete and the clay deposits contain volumes of unaltered granite. Furthermore, veins of tourmaline, quartz and greisen often cut the kaolinised granite in all directions with irregular frequency. Mining and processing methods therefore have to be used to remove the unaltered granite and the contaminating minerals.

The largest pits produce up to 11,000 tonnes per week of clay which is pumped via landing lines to central refining plants where it can be blended with clays from other pits to produce the desired marketing requirements (Fig. 2).

During the course of pit development, topsoil and overburden is removed by mechanical excavators, and scrapers; the top soil being subsequently stored for reclamation purposes.

Each pit has several operating faces where water from high pressure hoses is used to break up the clay matrix. The resulting washing stream gravitates to a central sink where centrifugal gravel pumps lift the clay suspension, also containing mica, quartz and feldspar, out of the pit to spiral classifiers which remove the sand, which is then conveyed to tips. These sand tips, which originally formed the classic *white pyramids*, are in the process of being landscaped and seeded.

The clay slurry is then passed through 36 cm hydrocyclones to remove the fine mica having a particle size diameter greater than 300 mesh, which in turn is pumped to storage lagoons.

A typical relationship between the clay and the waste produced as a result of mining operations is given in Table 2.

Table 2: Distribution of clay and waste taken from a pit

Product	% of Total Dry Material Removed
Sand	61 %
Micaceous Residue	13 %
Rock & Overburden	13 %
Clay	13 %

Prior to refining, the clay is stored in dewatering tanks where it is thickened. The water is then pumped to hosepools ready for use in the pit.

The pure kaolinite is associated with the finer region of the particle size distribution of the raw clay and conseqently refining is carried out by hydro-separation. Each central refining plant has several sets of hydro-separators having up to four successive stages, which overflows a product of 45 % less than 2 microns and 15 % greater than 10 microns.

Depending on its physical and chemical properties, this product is suitable either for sales as a filler or ceramic grade clay, or it can be refined even further by centrifuge to give a coating clay product of 75 % less than 2 microns and 0.5 % greater than 10 microns. Flotation methods can also be used to convert the centrifuge residue into a potential filler clay product.

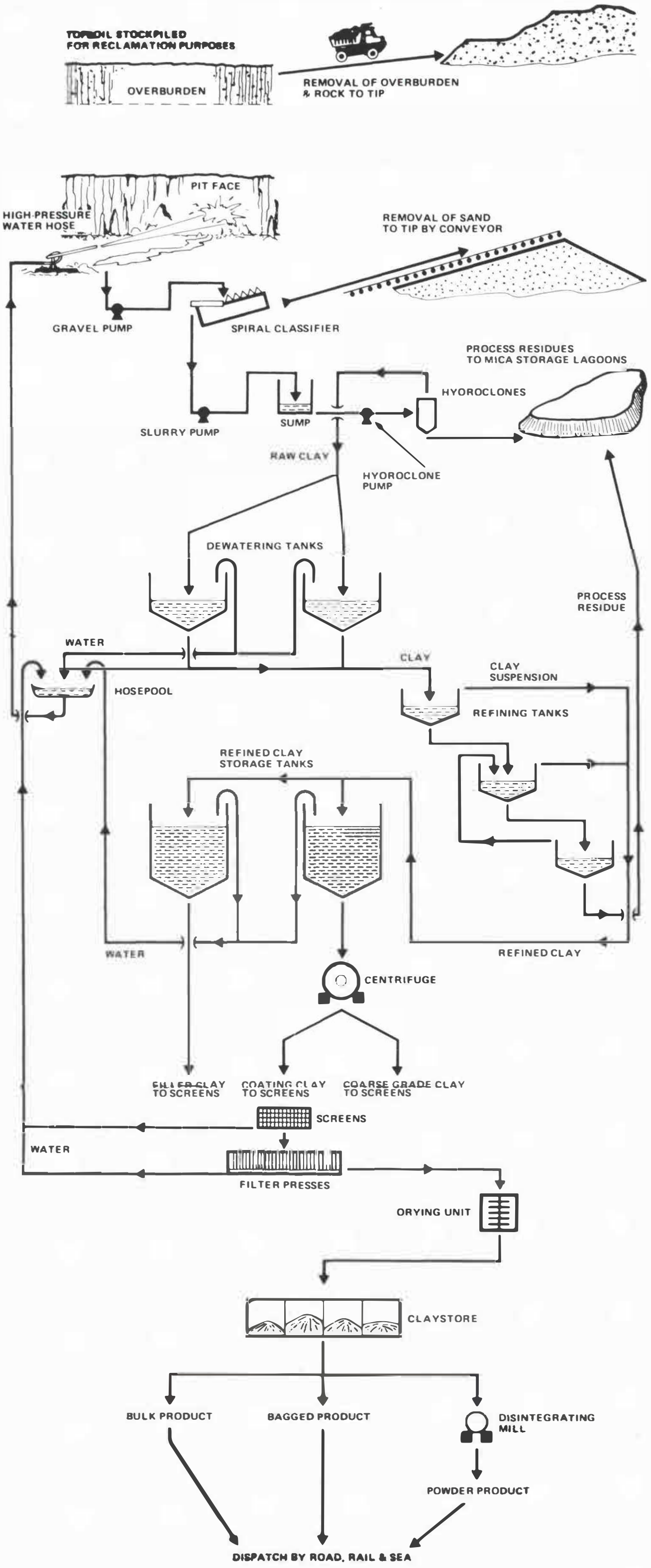

Fig. 2: Simplified flow diagram of china clay processing

Certain coarse clays for the paper filling industry are dewatered direct through a tube press to give a 18 % moisture product but, for the other systems, the incoming clays are filter pressed before being fed to the dryers which produce a 10 % moisture product in general, depending on the market requirements.

The clay is then stored in linhays before being transported by road and rail to UK customers or to the ports where it is shipped overseas.

1.3 Exploration and Quality Control

New deposits are located by using indirect geophysical gravity and resistivity methods and then diamond drilling is used to confirm the reserves, the overall geometry and quality of the deposit. Drilling is also carried out in areas which are currently being worked, usually on a 100 m grid and the information gained is used for planning pit development. Laboratory testing of the cores is carried out on a 3 m incremental basis where the properties of the clay are usually assessed at two levels of refining; equivalent to that for filler and coating products.

A considerable amount of testing is carried out at the production area laboratories, to monitor the properties of the clay before and after refining, after blending and at the final product stage. In addition to this, some of the larger clay pits make use of tests on daily samples taken from their operating faces and the information provided is used to considerable advantage for short term scheduling purposes.

1.4 Supplementing Existing Quality Information

Each year the clay pits produce in the region of 2.7 to 3.1 million tonnes of refined clay and the current methods of processing and quality control enable specifications of the market to be attained. As with any mineral industry there is always a need to supplement the existing information on its resources and it was to this end that a series of experiments were carried out to examine the extent to which further information can be derived from borehole sample results using mathematical techniques.

2. Earlier Experiments

2.1 Mineralogical and Mathematical Trends

The first experiments to be carried out were aimed at determining trend relationships within the properties of groups of borehole samples. An example of this work was carried out in 1973 when, after applying conventional statistical techniques to the data in the form of regression analyses, it was impossible to detect any meaningful mathematical trends; nor was it possible to quantify any relationship between different clay properties. However, it was obvious to the eye of the geologist that the samples did indicate variation which was related to geological trends in the area.

2.2 Comparing the Properties of Different Types of Samples

A dry mining exercise at a small pit in 1975 offered the opportunity for carrying out an experiment to compare the properties of three types of samples. Standard techniques, such as calculating simple averages and standard deviations or weighting by a *zone of influence* as in the *polygonal method*, were applied to the properties of the borehole samples within the vicinity of the pit and the results were compared to the properties of bulked matrix samples and bulked wash samples that had been obtained during the course of mining. However, with every technique that was used the comparisons made were inconclusive in a statistical sense, owing to the greater variability of the properties of the borehole samples compared to that for the bulked samples.

In retrospect, the reason for this is clear: borehole samples simply examine the properties of the clay at specified positions whereas the bulked samples, regardless of whether they are of pitwash or of dry matrix, *average out* a considerable amount of the inherent variation in the material.

The important lessons learnt from these early experiments were that conventional statistical methods can not be applied rigidly to borehole samples and that different methods of sampling are not always compatible. One other notable point was the disparity between statistical and geological interpretations of certain concepts, e.g., *trend* and *relationships*. With this factor in mind, a decision was made to set up a small team consisting of various working disciplines to enable a greater degree of cross-fertilization of ideas to be achieved and the degree of success in the subsequent experiments resulted mainly from this team approach.

3. Geostatistical Methods

3.1 Concepts as Applied to China Clay

Following the completion of the experiment discussed above, a review of current literature was carried out by the author in order to examine alternative applicable techniques. The type of method envisaged was one which combined the powers of mathematics with the important mineralogical characteristics of the deposit being examined and it became evident that the concepts of geostatistics were a suitable starting point for subsequent experiments.

The two major features of a borehole sample taken from a china clay deposit are its location in the area being drilled and the magnitude of the property that is being examined. The diameter of the core and also its orientation with respect to the plane of the orebody, two other important characteristics of a sample which theoretically have to be taken into account, are constants in this instance as a constant barrel diameter of 2.75″ is used and the holes are always drilled vertically into the deposit.

3.2 Techniques Used

The fundamental principle of Geostatistics is that the assay values of samples taken from an orebody are related with respect to their relative locations: e.g. in general, two samples taken 20 ft apart have assay values of closer similarity than those for two samples taken 40 ft apart.

3.2.1 The Semivariogram

The relationship between the assay values of adjacent samples can be expressed mathematically by the semivariogram which indicates changes in the variability of assay values with increases in the sample spacing.

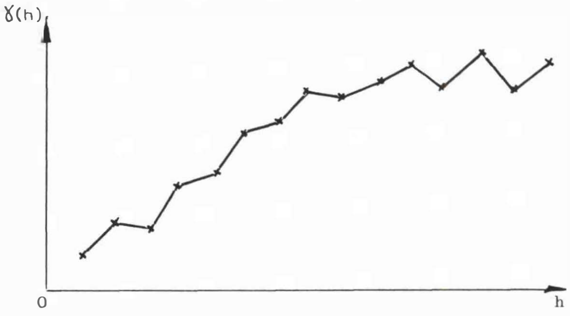

Fig. 3: Constructed semivariogram

A semivariogram is usually constructed (Fig. 3) by means of Equation (1):

$$\gamma(h) = 0.50 \sum_{i=1}^{i=N(h)} \left|f(x_i + h) - f(x_i)\right|^2 / N(h) \qquad (1)$$

Where:

$\gamma(h)$	semivariance for assay values at a spacing of h
$f(x_i)$	assay value at the position x_i
$f(x_i + h)$	assay value at a distance of h from x_i
$N(h)$	number of comparisons made at a lag of h.

The Spherical or Gaussian scheme (Fig. 4) is the most commonly used mathematical model for the semivariogram and is of the form given below:

$$\gamma(h) = C_0 + C_1\left[\frac{3}{2}\left(\frac{h}{a}\right) - \frac{1}{2}\left(\frac{h}{a}\right)^3\right] \quad \text{for } h < a \qquad (2)$$

$$= C_0 + C_1 \qquad \text{for } h \geq a$$

where:

a	range of influence of the samples, i.e., the distance beyond which there is no general relationship between the assay values
C_0	Nugget variance, attributable very often in practice to the size of the sampling interval and experimental errors in laboratory testing
C_1	the Sill
$C_0 + C_1$	total variation of the assays within the deposit.

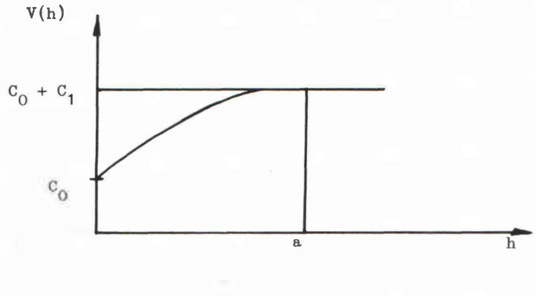

Fig. 4: The Spherical Scheme

3.2.2 Kriging

This is the name given to the process by which weighting factors are assigned to the assays of surrounding samples in order to estimate the properties of the material to be extracted from a given volume of ore. The procedure involves the solution of simultaneous equations

$$\begin{bmatrix} \gamma(S_1, S_1) & \gamma(S_1, S_2)\ldots\gamma(S_1, S_N) \\ \gamma(S_2, S_1) & \gamma(S_2, S_2)\ldots\gamma(S_2, S_N) \\ \\ \gamma(S_N, S_1) & \gamma(S_N, S_2)\ldots\gamma(S_N, S_N) \\ 1 & 1 \qquad\qquad 1 \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \\ \lambda_N \\ \lambda_0 \end{bmatrix} = \begin{bmatrix} \bar{\gamma}(S_1, V) \\ \bar{\gamma}(S_2, V) \\ \\ \bar{\gamma}(S_N, V) \\ 1 \end{bmatrix} \qquad (3)$$

Where:

$\gamma(S_i, S_j)$	Variance between the samples S_i and S_j
$\bar{\gamma}(S_i, V)$	Variance between the sample S_i and the volume to be extracted, V
$\lambda_1, \lambda_2 \ldots \lambda_N$	the weights to be assigned to the samples $S_1, S_2 \ldots S_N$, respectively
λ_0	weight assigned to the overall average property of the deposit. Calculations of the variances are performed with reference to the semivariogram.

3.3 Design of the Experiments

The success or otherwise of a geostatistical evaluation depends on the ability to obtain a meaningful semivariogram of the sample results. Consequently, the experiments to be described below were so arranged that they were *tailor-made* for semivariogram calculations.

4. An Investigation of the Inherent Variation in China Clay Properties

4.1 Objectives

The object of this experiment was to examine whether meaningful spacial relationships between samples could be found by deriving semivariograms for each of the clay properties examined, how these related to the geological features of the area and the changes that resulted with subsequent levels of refining.

4.2 Sampling and Testing

A site was chosen which had a well defined geological structure and where an experiment could be carried out without hindering normal production operations. There were three other important considerations, namely, cost, a sufficiency in the number of samples, and a pattern of drilling which would hopefully guarantee that some form of spacial structure could be identified. Consequently, a sequence of 120 holes were drilled at intervals of 5 ft in a cross shaped pattern which was aligned as far as possible to the major structural trend in the area. To ensure consistency in sampling, the area was levelled before sampling and each hole was drilled to a depth of 5 ft. Minimal drilling costs were ensured by using a modified Vole drill with an air-percussion coring device and the whole process was completed within two weeks.

The samples were tested in the laboratory for their basic properties at three stages in the process chain in the manner shown in Table 3. A subjective mineralogical examination of the dry matrix and the 300 mesh residue was also carried out to provide information on such characteristics as grain size, degree of kaolinisation and the presence of various types of mica.

Table 3 — Laboratory Testing of the Samples

Laboratory Procedure	Simulated Process
1. Matrix samples reduced to slurry form	Operation at the working face
2. Slurry screened at 85 mesh	Classification
3. Screened at 300 mesh •Properties of product examined	Hydrocloning
4. Allowed to settle at a rate of 30 min/ft of suspension •Properties of product examined	Hydroseparation
5. Product of 4 allowed to settle at a variable rate to give a product having the particle size distribution of a coating clay •Properties of product examined	Centrifuging

4.3 General Results

The semivariograms of each property (e.g. Fe_2O_3, K_2O, brightness and viscosity) were calculated using Equ. (1) and, in each case, a meaningful spacial pattern was obtained for both axes of the cross. Moreover the basic patterns obtained for the 300 mesh samples were reflected at the subsequent refining levels showing that, while the level of the property was affected by refining, the intrinsic spacial relationship between the samples had not been destroyed. It is not possible here to describe all the results in detail and the discussion which follows is therefore limited to the properties of yield, particle size, degree of kaolinisation and the presence of mica. The constructed semivariograms of these properties showed that the nature of variation in the drilled area was anisotropic (i.e., different variation patterns were found for each axis of the cross) and that there was a definite relationship between the properties of the clay products and the mineralogy of the deposit.

4.4 Degree of Kaolinisation

The degree of kaolinisation, a subjective assessment by the geologist, was given a numerical code between 1 and 7 depending on the extent of decomposition of the granite. The semivariograms which were produced (Fig. 5) highlight the anisotropy which was present in the deposit. It can be seen that in the line approximately parallel to the main geological trend, a gradual progressive change in the degree of kaolinisation. However, although there is a definite increase in variation between samples up to distances of approximately 100 ft, the samples at each end of the line perpendicular to the trend are of the same degree of kaolinisation.

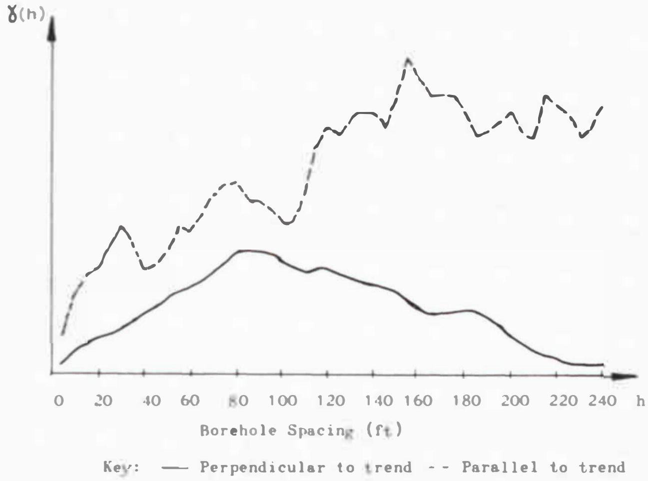

Fig. 5: Semivariograms of the degree of kaolinisation

4.5 Presence of Mica

Numerical codes, which related to the known general affect of each type of mica on clay properties were also assigned to each sample, e.g., a value of 1 was assigned in cases where no mica was detected whereas samples containing biotite micas were assigned a value of 4. Although this method sounds arbitrary, it is interesting to note the shapes of semivariograms which were obtained (Fig. 6). These indicate that along the line of samples parallel to the geological trend there was a repeated sequence of similar types of mica whereas there was a gradual progressive change in the type of mica present in the line of samples perpendicular to it.

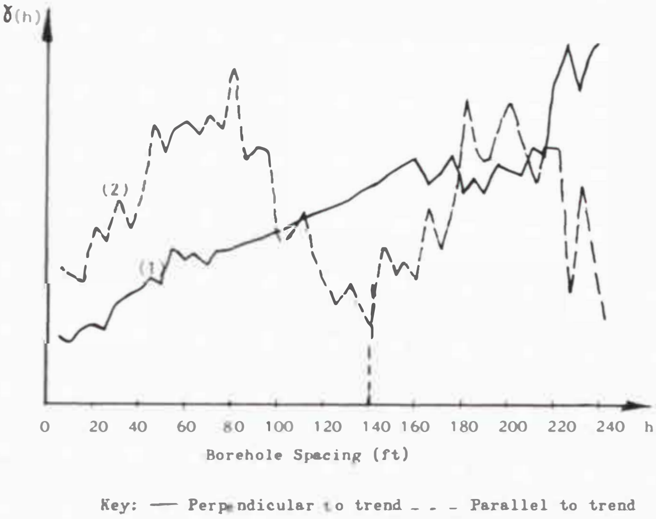

Fig. 6: Semivariograms of presence of mica types in the matrix

4.5.1 Particle Size

It has already been explained above that the processing of the matrix is geared to removing the coarse fraction by refining, as the pure kaolinite is associated with the finer particle size range. Consequently, a coating clay product consists mainly of kaolinite particles with small amounts of very fine (secondary) micas and other associated minerals.

The semivariograms of the < 2 micron fraction of the samples have been drawn to the same scale, to show the change in spacial behaviour which is due to refining. Parallel to the geological trend, as can be seen in Fig. 7, there is a poorly defined pattern of variation in this property at the two earlier levels of refining. If the scale is exaggerated, however, a more pronounced pattern is produced for the coating clay fraction which strongly resembles the corresponding semivariogram obtained for the micas as shown in Fig. 6.

Perpendicular to the geological trend, the shape of the semivariograms of the < 2 micron fraction is much more pronounced at the earlier stages of refining (Fig. 8). In the case of the coating product, the semivariogram produced shows that this relationship, which existed between the samples up to a distance of 140 ft, has been destroyed. For distances over 155 ft, there is some evidence of drift, showing that there was a general difference in the fine fractions of the samples in their product form at the two ends of the line. Although not as evident for the line of samples parallel to the main geological trend, there is also a resemblance between the general shape of this semivariogram and the corresponding one for the micas present in the original matrix.

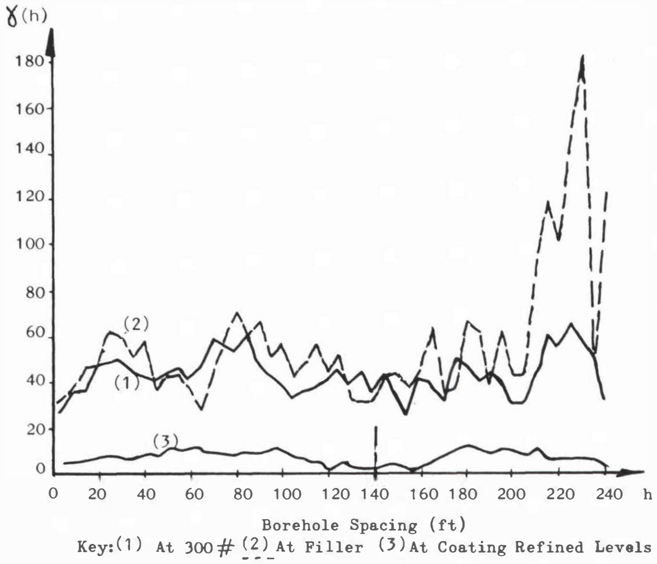

Fig. 7: Semivariograms of % < 2 microns particles parallel to trend

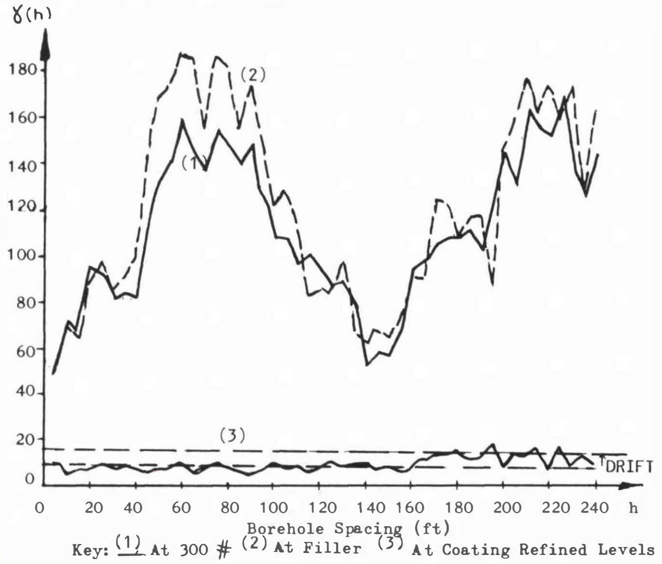

Fig. 8: Semivariograms of % < 2 microns particles perpendicular to trend

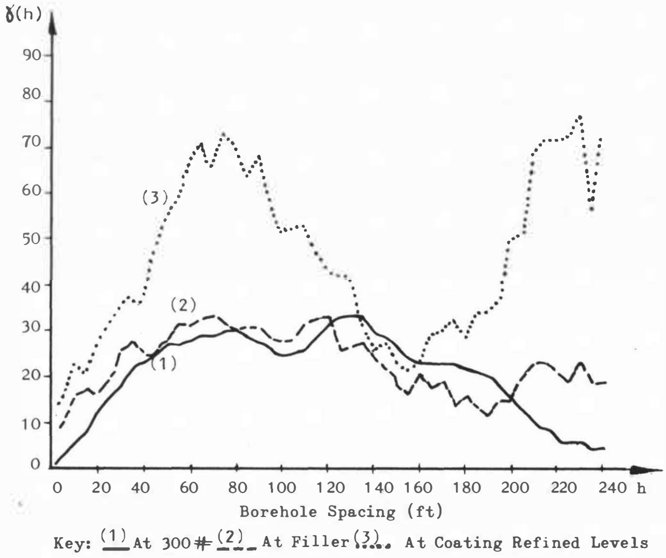

Fig. 9: Semivariograms of % yield perpendicular to trend

4.5.2 Yield

The general relationship between yield and the degree of kaolinisation is well known in the china clay industry, in that higher yields are associated with fully kaolinised granite. The semivariograms of yield (= product as a percentage of the original matrix) demonstrate this at the 300 mesh stage of refining (Figs. 9 & 10).

The underlying pattern in the variation was present at the filler refined stage although, for both lines of samples a degree of randomness was reflected which can be attributed to differences in the grain sizes of adjacent samples even over small distances

However, at the coating level of refining, there is an apparent lack of spacial relationship between the samples parallel to the geological trend whereas, for the line perpendicular to it, the semivariogram shows a definite structure indicating a repetition in the magnitude of the yields obtained from sequences of the samples. In fact there is a very strong resemblance between the shape of this semivariogram and the corresponding semivariograms for the 2 micron fractions at 300 mesh and filler.

4.5.3 Interpretation

By using the semivariograms it was possible to show that the samples obtained had a spacial dependence for each of the properties that were studied, that it varied according to the alignment with the major geological trends in the area and that, for certain physical properties, progressive levels of refining often removed this original relationship but produced a secondary spacial dependence. Furthermore, by

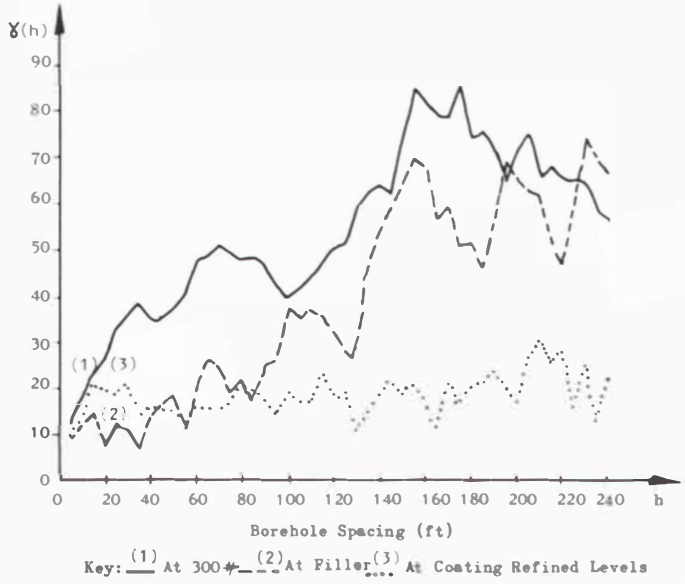

Fig. 10: Semivariograms of % yield parallel to trend

comparing the shapes of the semivariograms, relationships could be demonstrated between different clay properties.

In fact, these spacial co-relationships proved to be much stronger than those found by the conventional statistical methods of correlation and analysis of variance.

Discussions with the geologists involved on the work concluded that these indications were valid in that while there is no rigid mathematical relationship between the properties, there is a loose but definite relationship which is due to the way in which the deposit was formed.

In the examples that have been described, the degree of kaolinisation gradually increased along the major geological trend destroying the original feldspars in the granite to produce kaolin and secondary micas. With less intense kaolinisation, the original matrix micas were not altered. Consequently, there are repeated sequences of similar types of mica in this plane. In the plane perpendicular to it, however, the effect of decomposition on the original micas was not so drastic with the result that the semivariogram obtained reflects their presence.

During the course of 300 mesh and filler refining this coarser mica and minerals such as tourmaline and quartz were removed, so that the proportion of product is strongly related to the degree in kaolinisation. When the samples were subsequently refined to a coating product, a variable settling time was used to produce a *consistent* particle size distribution. The yield of product at this level is therefore related to the finer fraction of the feed, which was fairly uniform in the plane parallel to the geological trend but had a well defined variation in the plane perpendicular to it. As the finer fraction of the coating product produced a similar shaped semivariogram to those for the presence of mica, there is a reason to conclude that the secondary micas created during the process of kaolinisation are fine enough to be present in the coating product.

4.6 Summing up

This experiment showed the power of geostatistics in highlighting previously unquantifiable relationships between the properties of borehole samples and the geology of the china clay deposit. However, it was not possible to test the predictive capability of the geostatistical approach by mining the area and, consequently, a second experiment was set up in a large working pit where it was possible to stage a small scale mining exercise during normal production operations.

5. Examination of the Predictive Capabilities of Geostatistical Methods

5.1 Sampling and Testing

A suitable site to carry out the experiment was selected in one of the largest coating clay producing pits, where an excellent working relationship had developed between pit management and members of the team during the course of related projects. Taking into account the area of ground available and the minimum number of samples desired, 31 holes were drilled using a Boyles BBS 20 rig at positions shown in Fig. 11 to a depth of 40 ft at intervals of 20 m which conformed to a grid which was orientated so as to coincide with the underlying geological features in the area. However, before drilling was carried out, the site was levelled in order to remove a layer of sand that had built up as a result of washing operations at neighbouring working faces.

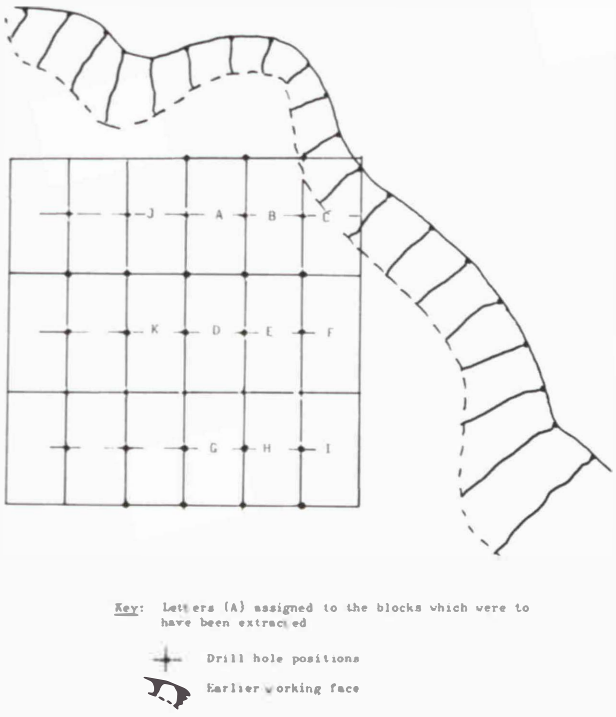

Fig. 11: Positions of drill holes and mining blocks in second experiment

Bearing in mind that the intention of the project was to test the accuracy of the geostatistical estimates against the properties of the clay actually extracted, the cores were divided for laboratory testing into incremental lengths of 20 ft, so as to conform to the height of the working faces in that part of the pit. An examination of their properties at filler and coating refined levels was subsequently carried out.

5.2 Construction of the Semivariograms

In order to estimate the average properties of the clay to be *extracted* from the area (as opposed to the average properties of *samples* obtained from the area), the effect of product yield had to be taken into account in the geostatistical analyses. As special care had been taken to ensure that the samples had all been drilled to the same depth a second potential variable, i.e., volume of matrix, had no affect on the analysis.

Consequently, the geostatistical analysis on each property concerned involved 5 steps:

1. Calculating semivariograms for the product, yield x property.
2. Calculating semivariograms for yield.
3. Estimating the average value of yield x property of clay from a given block of matrix, by Kriging.
4. Estimating the average yield of clay from the same block of matrix using Kriging.
5. Dividing the estimates in 3. by that of 4.

The semivariograms obtained in this experiment involved much larger spacings and fewer comparisons between samples than in the previous one and for this reason, an average semivariogram was obtained in each case regardless of anisotropy. For most properties, the spacial relationship between the samples was very strong as can be seen, for example, in Fig. 12, and spherical models were subsequently fitted. In the example shown the models fitted were:

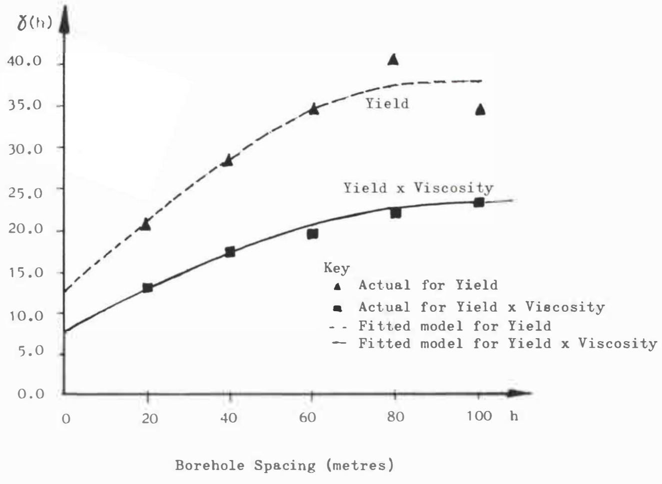

Fig. 12: Model semivariogram for yield and yield x viscosity

1. For yield x viscosity

$$\gamma(h) = 7.5 + 15.5\left[\frac{3}{2}\left(\frac{h}{93}\right) - \frac{1}{2}\left(\frac{h}{93}\right)^3\right] \quad h < 93 \text{ metres}$$

$$= 23.0 \quad h \geq 93 \text{ metres}$$

2. For yield

$$\gamma(h) = 12.5 + 25.0\left[\frac{3}{2}\left(\frac{h}{87}\right) - \frac{1}{2}\left(\frac{h}{87}\right)^3\right] \quad h < 87 \text{ metres}$$

$$= 37.5 \quad h \geq 87 \text{ metres}$$

5.3 Use of Kriging

With regard to subsequent extraction of the clay matrix and the monitoring of its properties, a decision had to be taken regarding the extent to which the area of the site should be divided for Kriging purposes. An estimation of the whole volume of matrix would give no measure of quality fluctuations whereas, by splitting the area into a large number of small blocks, estimates of quality fluctuations could be reasonably precise but the blocks themselves would be too small to mine. A compromise decision was therefore taken and blocks 20 m by 40 m (20 ft in depth) were examined. These divisions are shown in Fig. 11.

The estimates of the properties in each block were obtained by means of a computer program and, in each case, the statistical error of estimation was calculated using Equ. (4).

$$\frac{\sigma^2_p}{\mu^2_p} = \frac{\sigma^2_y}{\mu^2_y} + \frac{\sigma^2_{(y\times p)}}{\mu^2_{(y\times p)}} - \frac{2\,\varrho\,\sigma_y\,\sigma_{(y\times p)}}{\mu_y\,\mu_{(y\times p)}} \qquad (4)$$

where:

σ_p	error of estimating the property from the block
σ_y	error of estimating the yield from the block
$\sigma_{(y\times p)}$	error of estimating the value of yield x property
μ_p	average property of the area in the experiment
μ_y	average yield of the area in the experiment
$\mu_{(y\times p)}$	average value of yield x property of the area in the experiment
ϱ	correlation coefficient of yield and yield x property.

A typical value of the error obtained for the viscosity of a block was 2.6 units which was approximately 4 % of the estimate.

5.4 Dry Mining and Sampling

Following the evaluation of the properties, a Caterpillar D8 was used to remove each block separately to a position some distance from the remaining blocks to avoid possible mixing. The matrix was then washed in the usual manner and sampled every thirty minutes. Bulk samples, representing six hours wash were then tested for their properties. Unfortunately, owing to pit development constraints and the time available, it was only possible to remove six of the blocks, but excellent comparisons between the washed samples and block estimates were found, as demonstrated in the case of viscosity in Table 4.

Table 4: Comparison between predictions and wash results

Name of Block	Predicted Viscosity Measurement	Average of Bulk Samples
K	65.3	65.0
D	64.5	64.4
J	66.6	66.3
A	65.8	66.7
B	65.3	64.7
E	55.2	56.1

5.5 Summing up

The results obtained in the experiment were given an enthusiastic response by senior production management, despite the fact that only six of the blocks had been used for comparisons. Moreover, the estimates for the remaining blocks tied in firmly with the pit management's own *feel* for the area. Consequently, production management and the geological section reached a decision to apply geostatistical techniques to existing borehole information within the Company.

6. Current Use of Geostatistics within English China Clays

6.1 Home Deposits

Following the success of the two experiments described in Sections 4 and 5, the use of geostatistical methods has been accepted by the Company. The techniques are currently being applied to the available borehole information in the major clay producing pits in Cornwall and Devon to supplement existing knowledge on the quality variation within the deposit as a further aid to planned pit development. In certain cases, the positions of additional boreholes have been recommended where the presence of clay has been indicated in areas of a deposit, previously treated as being barren.

As the projects are now being directed towards areas where volumes of the deposit have been extracted after most of the boreholes were drilled, considerable care has to be exercised in reserve calculations using the geostatistical techniques. The method used consists of dividing the deposit into several 12 m horizontal levels. With reference to their collar elevations, the borehole incremental results are matched with these levels and the appropriate ones are averaged together. Semivariograms of these results are then calculated and Kriging techniques are applied to each property and a *model* of the deposit prior to extraction is then constructed. It is only after this stage has been completed that those areas that have been extracted are removed from reserve calculations.

The use of computers is extremely important as an average of 180 boreholes are involved in each geostatistical project, and a *suite* of computer programs has been written to carry out the many tedious calculations. With the advent of microcomputer technology these programs have been transferred from the Company's mainframe computer to the Operational Research Section's microcomputer and this has reduced the time involved on a particular project considerably.

6.2 Other Deposits Within the E.C.C. Group

Projects using Geostatistics have also been carried out to a large degree of success on overseas china clay deposits in Georgia, USA and Brittany in France. While the techniques used have basically remained unchanged, revisions in the computer programs have been required to take into account different sample testing procedures that were used.

Most recently, however, the use of geostatistics has been extended to a Ball Clay deposit in North Devon, where a pilot experiment on reserve assessment is showing encouraging results.

6.3 Final Comment

In conclusion, during the past four years geostatistics has been shown to be an extremely valuable aid and has therefore gained acceptance within the Company. In all projects, the work carried out has involved the joint efforts of the geological and operational research staff to ensure that the results obtained are meaningful and can be used practically.

References

[1] Menadue, K.J., "Developments in the China Clay Industry in Cornwall", IMM Transactions, April, 1979

[2] Royle, A.G., "A Practical Introduction to Geostatistics" Unpublished course notes, University of Leeds, 1976

[3] Clark, I., "Practical Geostatistics", Applied Science Publishers, 1976

Acknowledgements

The author is grateful to T.J. Skelton, Production Director and J. Potter, Production Manager of E.C.L.P. & Co. Ltd., for permission to publish this paper and extends his gratitude to colleagues, in particular to Dr. C.W. Gronow and A.D. Francis for their help and encouragement.