Comparison of grade modelling methods at Blackpool china clay pit, Cornwall

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Two methods of estimating grade data are compared: implicit modelling (using Radial Basis Functions) and explicit modelling (using Ordinary Kriging). Residuals are defined in order to improve the comparison between the different models. As a case study, these methods are applied to a kaolin resource at Blackpool Pit, St Austell, Cornwall. Although Blackpool pit is not currently in operation, the area could be developed in future. The two estimates produced are globally very similar but the residuals identify areas of significant difference, likely due to the highly variable nature of the kaolinisation at these locations. Residuals can be used to identify areas that warrant further sampling and can be used to delimitate the error attached to an estimate.

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Introduction

Modelling the geology and interpreting grade data is an essential part of modern mining operations with a variety of different software tools available. Traditionally, geological models were constructed entirely manually by creating volumes that only contained what was deemed to be geologically similar material. This process had certain advantages: for example, each drillhole could be evaluated individually and mistakes are often easy to spot. However, it was also a time-consuming process. More recently, less manually intensive ways of constructing grade shells have been developed using radial basis functions first described by Cowan *et al*. (2003). The uptake of this type of modelling has been particularly strong in Australia (e.g. Hill *et al*., 2014; Rawling *et al*., 2006). While it is now starting to gain global acceptance as an alternative to traditional orebody modelling, it can also complement the traditional techniques. See, for example, Knight (2006) and Kentwell *et al*. (2006).

Comparisons between Radial Basis Function Modelling (RBFM) and Ordinary Kriging (OK) are often based on theoretical considerations and use relatively simple datasets (Stewart *et al*., 2014). Alternatively, RBFM and OK are compared after OK has been constrained within user-defined domains (Kentwell *et al*., 2006). This study aims to apply and compare RBFM and unconstrained OK in the case of a kaolin deposit.

Kaolin, known locally as china clay, has been mined in the St Austell area for the last 250 years (Bristow, 1993). The deposit was formed by kaolinisation of the granite pluton which outcrops to the north of St Austell, forming part of the Cornubian Batholith (Scrivener, 2006). The exact driver of kaolinisation is still unclear; it is possibly linked to both hydrothermal alteration along structures (mineralised in conjunction with the alteration and due to later fluid flow) and chemical weathering of the granite during geological periods of high rainfall and humidity (see Alderton and Rankin, 1983; Bristow, 1993; Sheppard, 1997; Psyrillos *et al*., 1998). Blackpool pit (Figure 1) lies within the central area of current clay mining. The pit is not currently in operation and has been allowed to flood.

Methodology

The practice of Kriging has become widely accepted as the method of choice to produce estimates of grade data from drilling or other sampling techniques (Isaaks and Srivastava, 1989). Kriging forms the integral part of the geostatistical package of techniques, where the spatial variability of a variable across a deposit is computed using the variogram. The variogram considers the variance between samples at different sample distances, based on the assumption that at a certain distance there will be no relatedness between samples. The basic workflow to produce an estimate by Kriging is as follows. Firstly, an experimental variogram is computed from the sample data. A mathematical model is then fitted to the experimental variorgram, following the shape produced by the experimental variorgram as closely as possible, so as to reflect most accurately the spatial variability seen in the data. The area to be estimated is then divided up into a series of blocks and Kriging then estimates the variable in each block from the known data points by applying a weighted average, with the weights derived from the variogram model. Kriging is optimised through various Kriging outputs which give a measure of how unbiased the estimates are. A good overview of the process of Kriging and how it is used by resource geologists is provided by Clark (1979).

Radial Basis Function Modelling uses a mathematical function as an interpolator to produce an estimate of a variable across an area. As in the case of Kriging, a model is fitted to the data, but for RBFM the fitting is normally done mathematically. A weighted average, with weights derived from the Radial Basis Function, is then used to estimate unknown points. The unknown points estimated can then be averaged into regular blocks to be used in further mine planning. An overview of how RBFM operates is provided by the producers of Leapfrog software by Aranz Geo (2015).

For the purpose of resource exploration and resource definition, Imerys Minerals Ltd. and previous companies have gathered a large dataset across in Blackpool pit. The data are distributed irregularly across the area and were obtained from

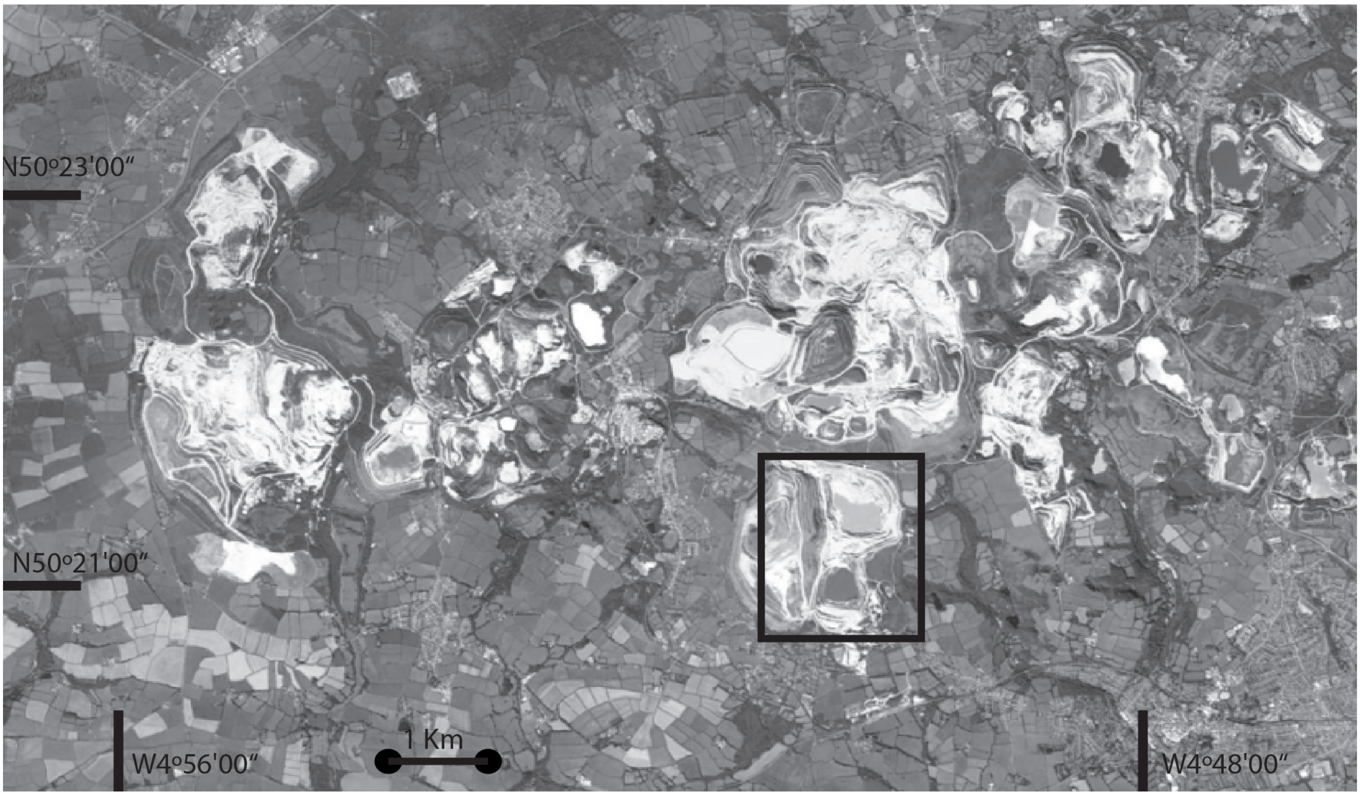

Figure 1. *Location of Blackpool china clay pit relative to the St. Austell china clay works. Map data ©2015 Google.*

samples extracted with four drilling techniques: diamond coring, rotary air blast, reverse circulation, and sonic drilling. The south-east area of the pit was chosen for study as this could be the focus of future extraction and there is sufficient diamond core (DC) drilling data to generate a resource model (Figure 2).

Using these data, block grade estimates derived from RBFM and OK were produced for a predefined area. Once the grade estimates had been generated, their use for further mine planning was compared in two different ways. In the first case, continuous grade data produced from the two methods were compared directly. In the second case, the grade data were grouped according to pre-defined cut-offs into areas of low, mid, high and very high grade. For mining and resource delineation purposes, Imerys Minerals Ltd. group the data into these categories, so the same procedure has been carried out here to make the results more comparable. The cut-offs used for the groupings are given in Table 1 and were defined by the percentages of material passing through a 15 μm sieve.

To investigate further the difference between the estimates generated, residuals have been calculated across the estimated area using the equation:

$$R = (\hat{v}_1 - \hat{v}_2)^2 \qquad (1)$$

where R is the residual for a particular block, $\hat{v}_1$ represents the first estimate generated and $\hat{v}_2$ the second estimate generated with the same co-ordinates.

Classification	Cut off	Code used for Plots
Very High	>19.9%	4
High	14.4% to 19.9%	3
Mid	10.4% to 14.4%	2
Low	<14.4%	1

Table 1. *Cut-offs used to group estimations. Values given as percentage of material that will pass through a 15μm sieve.*

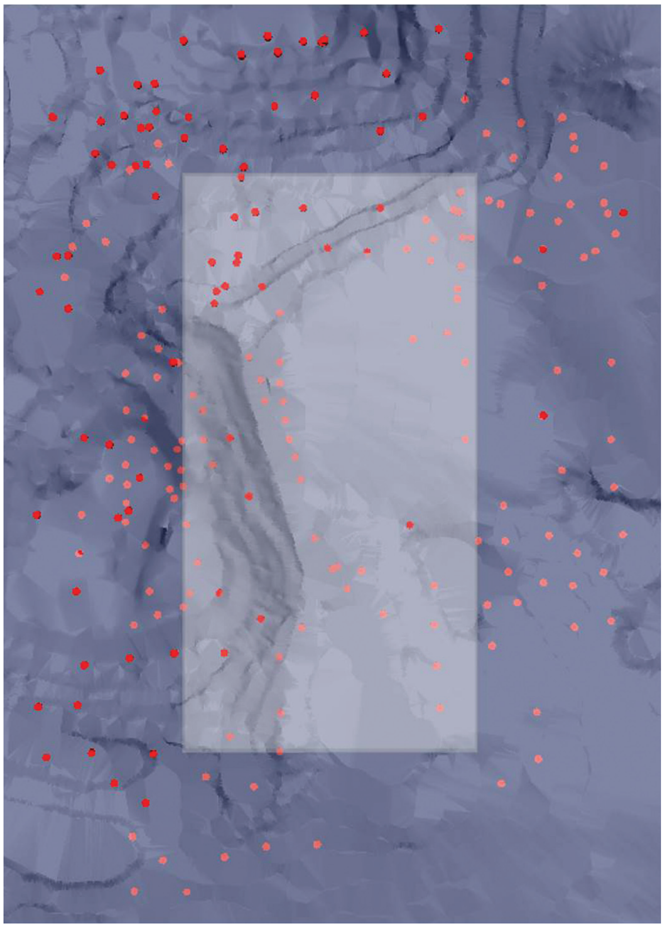

Figure 2. *Location of Diamond Core (DC) data relative to the estimated area.*

Results

The OK and RBFM estimates appear to be visually (Figure 3) and statistically (Figure 4, Table 2) similar. Within the south-east area, four subareas of higher grade are present: to the north east, on the western slope, in the centre, and in the south-east. The histograms show a positive skew, with the modal grade around 10% in both cases (Figure 4). Grouping the data reveals that the two methods estimate exactly the same amounts of high (3) and very high (4) data. There are differing amounts of low (1) and mid (2) grade data, with the mid grade being more common in the RBFM estimate and less common in the OK estimate. The correlation matrix (Table 3) indicates that there is a strong spatial correlation between the OK and RBFM raw and grouped estimates. Note that the correlation between the grouped estimates is slightly lower, which indicates that a

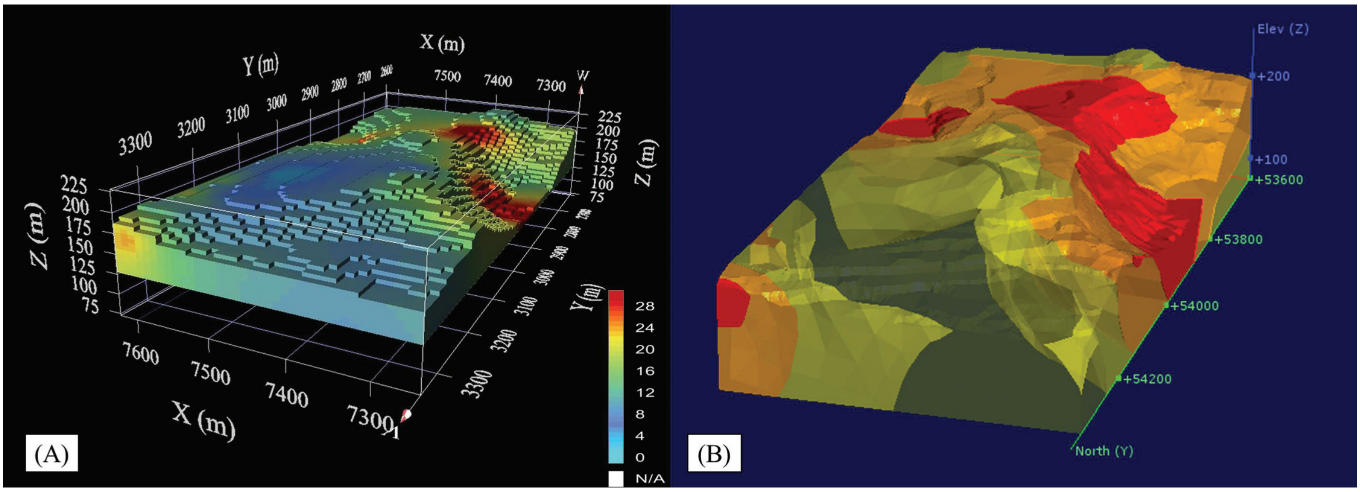

Figure 3. *Visualisation of estimates produced using Ordinary Kriging (OK) and Radial Basis Function Modelling (RBFM).* ***(a)*** *OK estimate produced in Isatis.* ***(b)*** *RBFM estimate produced in Leapfrog.*

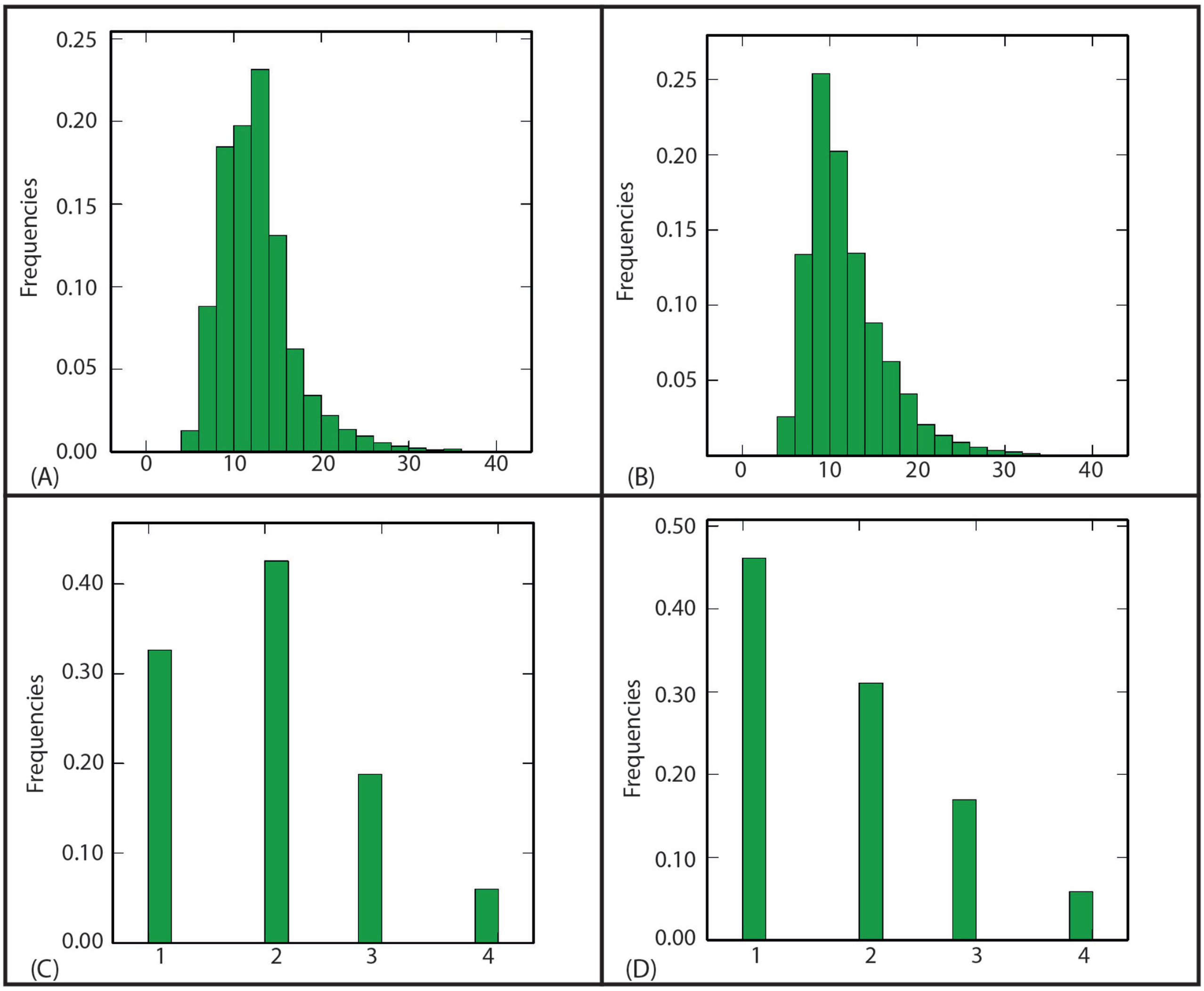

Figure 4. *Histogram of estimates and estimates grouped into grade classes.* ***(a)*** *Estimate produced using RBFM.* ***(b)*** *Estimate produced using OK.* ***(c)*** *Grouped estimate produced using RBFM.* ***(d)*** *Grouped estimate produced using OK.*

Estimate	Mean	Std. Dev.	Min.	Max.
OK raw	12.60	4.26	4.35	36.65
OK grouped	1.98	0.87	1	4
RBFM raw	12.54	4.77	3.45	39.1
RBFM grouped	1.99	0.93	1	4

Table 2. *Basic statistics of the raw and grouped estimates produced using Ordinary Kriging (OK) and Radial Basis Function Modelling (RBFM).*

		OK		RBFM	
		Raw	**Grouped**	**Raw**	**Grouped**
OK	**Raw**	1	0.92	0.87	0.78
	Grouped	0.92	1	0.8	0.77
RBFM	**Raw**	0.87	0.8	1	0.92
	Grouped	0.78	0.77	0.92	1

Table 3. *Correlation coefficients between the estimates and estimates grouped into grade classes produced using Ordinary Kriging (OK) and Radial Basis Function Modelling (RBFM).*

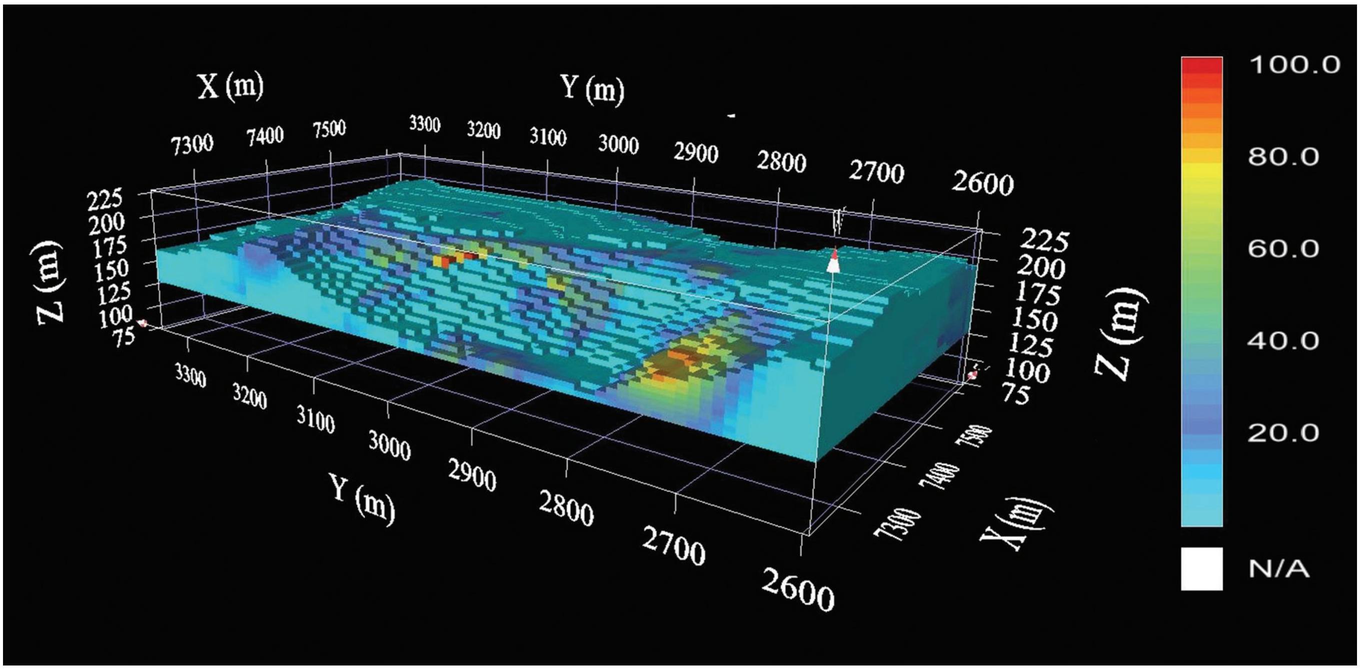

Figure 5. *Distribution of sum of the squared residuals between estimates produced.*

considerable proportion of the estimates are close to the predefined cut-offs.

Visual inspection of the residuals (Figure 5) indicates that the difference between the two estimates is not evenly distributed. The majority of blocks exhibit a relatively low residual of around 10, indicating that a difference of less than 4 exists between the estimates. Localised pockets occur where the residual is much larger, up to between 60 and 100. Most of the higher residual areas lie on the western slope of the study area and appear to be concentrated around the edges of the slope.

Discussion

The two estimates produced are significantly different when residuals are calculated. The cause of the difference between the estimates is unclear. A relationship to data density is unclear, with areas that contain sparse data and areas with plentiful data both exhibiting high and low residual values. The localised nature of the residuals implies that some areas are more inherently uncertain than others. The causes of this uncertainty could be either due to sampling errors, that make estimation unstable, or due to fundamental variability of kaolinisation. The latter is deemed to be more probable here as the geology in this part of the pit changes rapidly, making estimation problematic.

The residuals commonly display a gradual change, indicating that the uncertainty is generally diffuse where present. There are areas where the change from high to low residuals is much more abrupt, caused by significant differences in the two estimates at a local scale. Where this is the case, the cause is more likely to be due inaccuracies in the underlying estimation since these abrupt changes are geologically unlikely.

Conclusions

Simply comparing these two estimation methods does not indicate which one is the most appropriate to use. However, through observation of differences in the models, it is possible to infer the uncertainty attached to either estimation process. This can help to inform future drilling targets and reduce bias in the estimation process.

This study highlights the difference between estimates produced using different methods and a highly irregular dataset. Visually and statistically the models may appear to be very similar, but residuals show that significant variation exists. The cause of this variation is unclear but it is likely to be related to the highly irregular nature of the kaolinisation, which shows a high degree of variation over short distances.

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