Evaluation of Unfolding Techniques for Grade and Resource Estimation of Tectonically Deformed Deposits

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ABSTRACT

Unfolding of deformed deposits prior to grade and resource estimation is necessary in order to reconstruct the spatial distribution of grades at the time the deposit was formed and restore the relative positions of samples to their pre-deformed state. A number of different unfolding techniques have been developed and some of them are integrated in major mine planning packages. Recent methods are based on the use of an unfolded coordinate system for the transformation of every sample and estimation point. Their differences can potentially lead to significantly different grade estimation results and have a considerable effect on sample selection and consequently on the classification of resources. This paper aims at evaluating the effects of the application of different unfolding techniques to the spatial distribution of grade estimates and their classification in different resource categories according to reporting standards.

1. INTRODUCTION

Variography and grade estimation of deformed deposits due to folding or faulting present a complex geometrical problem. The spatial relationships between samples and blocks or nodes to be estimated are modified from their original values according to the geometrical characteristics of the folds and/or faults acting in the area of the deposit. Relative distances and directions between samples and blocks are not what they were in the original state of the deposit causing the grades or other qualitative parameters to present a less continuous behavior. The shifting of samples from inside the studied orebody according to the fold or fault geometry also means that sample selection to form pairs for variography or to estimate a block using a search ellipsoid is further hindered leading to difficulties in deriving an interpretable experimental variogram or downgrading of estimates classification due to lower number of available samples. In other words, the altered geometry of the orebody leads to problems in all aspects of grade and resource estimation, from variography to classification of resources.

There are also cases of orebodies where their geometry is not deformed post but during deposition due to the geometrical shape of the surface or void where deposition takes place, e.g. an undulating basin. In these cases, even though the samples are still in their original location, the change in orientation of the orebody calls for a method to alternate the search cone and search ellipsoid during variography and grade estimation respectively.

A number of methods have been developed over the years to restore the location of the samples relative to the points of estimation or the other way round. This paper presents three different ways of treating orebody geometrical deformities as implemented in one of the major mine planning packages (Vulcan 3D software, Maptek Pty Ltd):

1. Use of estimation domains with soft boundaries and application of a contact profile analysis tool,
2. Use of alternative local search regions,
3. Unfolding by tetra modeling.

Their methodology and application will be examined using a case study in the following paragraphs and a comparison will be made as to the produced resource estimates and classifications. The case study is based on an undulating stratigraphic copper deposit and a large number of reverse current grade control drillholes.

2. EXAMINED UNFOLDING METHODS

2.1 Use of Estimation Domains and Soft Boundaries

Prior to the development of unfolding techniques, the common practice was to split the orebody in several estimation domains defined by areas of the orebody where its orientation is more or less constant. This practice is still in use today in many cases where unfolding is considered to be too complicated to apply (particularly when it is not possible to model the required controlling surfaces) or where there are software limitations (unfolding is not available in the software package used for estimation).

Figure 1 shows how the case study orebody was divided to four estimation domains to account for changes in its orientation. Each domain was studied and estimated separately using different search ellipsoid orientations. In order to ensure continuity of grade estimates when crossing domains, it was possible to include samples from nearby estimation domains but with restricted search radius.

Sometimes samples that are at different estimation domains share similar grade properties close to the limit between the domains, known as a *soft boundary* between the domains. Thus, it could be useful to include samples from a different domain but only at short distances from the blocks in the current domain.

The Contact Profile Analysis (CPA) tool included in Vulcan was used to investigate the relationship between grades when moving from one estimation domain to another to improve the use of samples from neighbouring domains during estimation. Samples from each domain were paired with samples from a neighbouring domain based on a separation distance. The pairs were constructed over an increasing separation distance. For each separation distance, the average grade of the first domain was plotted against the average grade of the second. Average grades from the first domain were plotted on negative distances so the differences could be observed within the graph (Figure 2). Careful examination of the produced graphs allowed the determination of a safe distance or width for the soft boundary between estimation domains. Table 1 summarises the results from CPA.

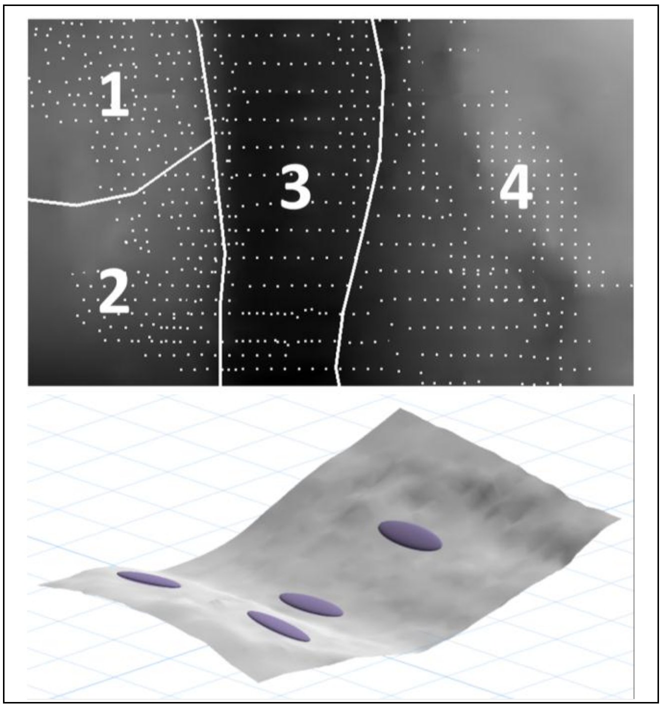

Figure 1: Plan view showing orebody hanging wall surface and boundaries of the four estimation domains (top) and 3D view showing search ellipsoid orientation for each domain (bottom).

Table 1: Analysis of soft boundary width using Contact Profile Analysis.

Soft Boundary	Domain 1-2	Domain 1-3	Domain 2-3	Domain 3-4
Distance	65m	25m	20m	22.5m

Each domain was estimated using samples only from that domain plus samples from a neighbouring domain up to the distance from their shared boundary as shown in Table 1. For example, domain 1 was estimated using samples up to 65m into domain 2 and up to 25m into domain 3. This way, some continuity of grades from one estimation domain to the next was maintained, and the blocks close to the boundaries between domains did not have a low sample count that would lead to low confidence resource classification.

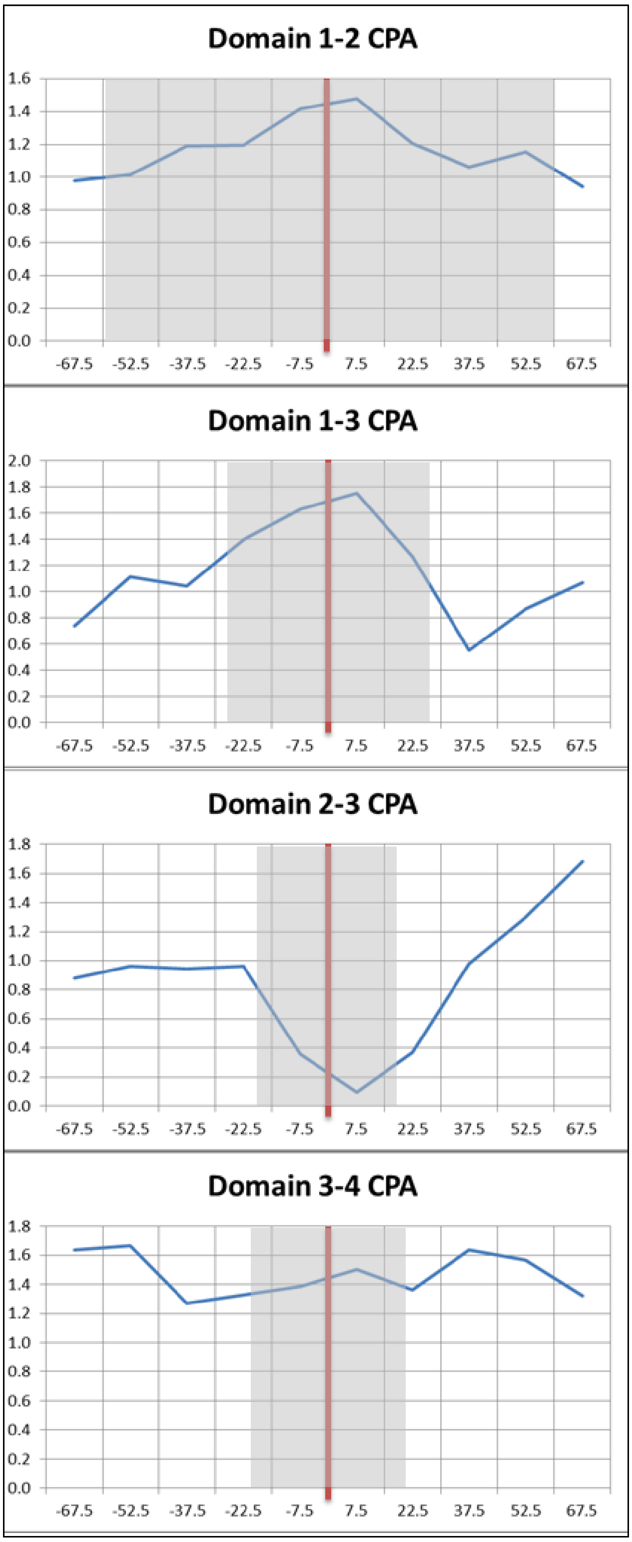

Figure 2: Graphs from contact profile analysis showing average grade of samples at increasing distances from boundary between domains.

2.2 Alternative Local Search Regions

The alternative local search regions method is based on the idea that each block to be estimated in the deformed orebody can have its own search ellipsoid defined using two controlling surfaces (hanging and foot wall) to derive appropriate bearing, plunge and dip values for the point at the centroid of the block. The closest distance between the two surfaces at that point can also be used to adjust the minor axis of the search ellipsoid.

This method requires the addition of three variables to the block (resource) model that will be used to store the bearing, plunge and dip of the search ellipsoid for each block, plus a fourth variable that can be used to store the minor axis of the search ellipsoid if required. Figure 3 shows how the search ellipsoid orientation changes from one block to another in cross section.

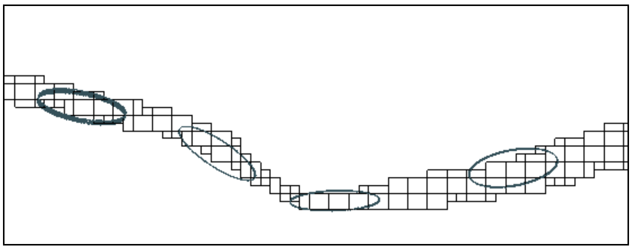

Figure 3: Section through block model showing alternative search ellipsoids used for sample selection during grade estimation.

As in the case of using estimation domains, no transformation of sample coordinates or relative distance is actually performed using the alternative local search regions method. However, the calculation of the alternative search ellipsoid orientations takes minimal time and once performed and the bearing, plunge and dip values are stored in the model, they can be used in any number of estimations at no extra time cost. Additionally to alternative local search regions, it is possible to calculate alternative centroid coordinates for the blocks to be used during estimation, in which case transformation of block coordinates relative to samples is actually performed.

2.3 Tetra Modelling

All volumetric geometries can be represented in 3D using a set of tetrahedra. Tetra modelling, the third and most advanced method discussed in this paper, uses the tetrahedron as the basic unit for representing volumetric geometry. A tetra model is composed of indexed 3D tetrahedra, in contrast to the set of connected flat triangles forming a standard triangulation. The hanging and foot wall of the case study deposit were used to create a solid 3D tetrahedral model (Figure 4).

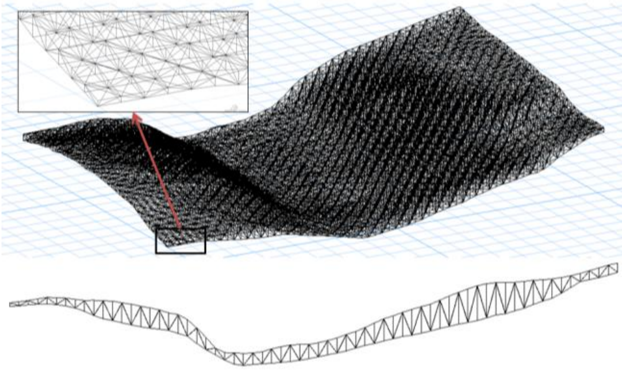

Figure 4: Visual representation of tetrahedral model in 3D (top) and cross-section (bottom) used to unfold sample locations.

This process is based on the generation of tetrahedra from the triangle points contained in the triangulation models of the controlling surfaces. The points are joined together to form tetrahedral shapes alternating in direction. Each triangle in the original two surfaces becomes a face in some tetrahedron in the resulting tetrahedral model. In cases when this is not possible, points are inserted (e.g. the midpoint of a triangle) to ensure that the original triangles do appear in the result. Further to this, each tetrahedron must not have all of its points coming from only one of the input surfaces. This requires internally rearranging the tetrahedra and possibly adding further points. The line segments generated pass through block model cells with one end point touching the hanging surface and the other end point touching the floor surface. The quality and resolution of the produced tetrahedral model depends on the point density of the limiting surfaces, especially in the areas where folding or faulting is more severe (Kapageridis, 2006).

A line of minimum distance (true thickness) is calculated for each block cell. The line of minimum distance is then used to define a 'mid-surface' between the hanging surface and the floor surface. This surface, referred to as a track surface in tetra modelling, is the path in three dimensions that the search ellipse follows, while maintaining the same ratio between the floor and hanging surface as a point selected from anywhere in the model.

The distances and angles of sample pairs (in variography) and between samples and blocks (in grade estimation) are calculated in the tetrahedral model space and not the Cartesian space. Following the successful generation of the tetrahedral model each sample point is located inside one tetrahedron. The coordinates in the tetrahedra are normalized so that the bottom surface has a Z of 0 and the top surface has a Z of 1. The space between the two surfaces has the original Cartesian coordinates and any number of other coordinate systems based on the tetrahedra. Different tetrahedral coordinate systems can be derived by starting at different places in the model. Neighbouring samples are found for each point, so that all pairs of points up to a radius of number of lags x lag size are found.

When passing from one tetrahedron to another, the incident angle from the old tetrahedron is converted to the coordinate system of the new tetrahedron. Keeping track of the apparent direction provides a bearing and distance. The Z coordinate (relative distance between the two surfaces) provides the tetrahedral Z coordinate. This process provides coordinates relative to the starting point. The end result is a search cone for building sample pairs and a search ellipsoid for selecting samples that is distorted and follows the track surface of the tetrahedral model.

The fundamental operation of unfolding using a tetra model during grade estimation is to list all samples inside a distorted ellipsoid centred at a given coordinate (Figure 5). So, given a coordinate, the tetrahedron containing that coordinate is located. Samples from that tetrahedron are added, that are inside the search ellipsoid. Neighbouring tetrahedra are searched for more samples which are inside the search ellipsoid. This process is repeated until all relevant tetrahedra have been searched.

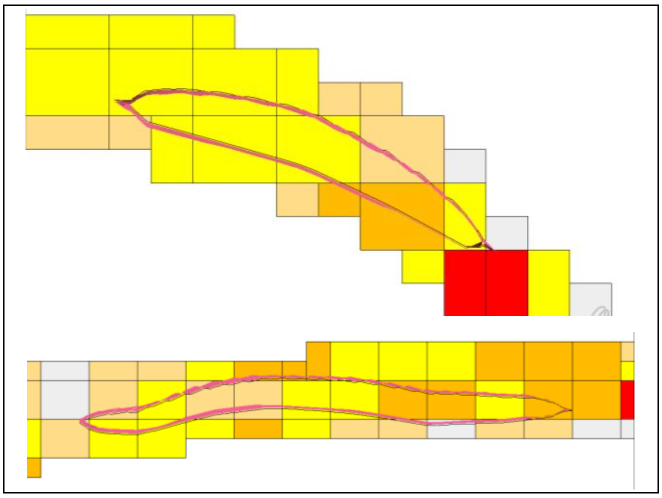

Figure 5: West-East (top) and North-South (bottom) cross section through block model showing distorted search ellipsoid used during grade estimation with tetra modelling.

3. EXAMINATION OF RESULTS

Separate estimation variables including grade, kriging variance and resource classification, were added to the block model to store the results from different methods of treating deformities. For the estimation domains and soft boundaries method, a domain variable was also added. Separate estimation runs were performed for each method and resource class. In order to compare the three methods on the same basis, the same variogram model was used in all of them, modeled without the use of tetra modeling. The same sample selection strategies were used in all methods corresponding to different resource classes as shown in Table 2.

Table 2: Estimation parameters for different resource classifications.

Class	Measured	Indicated	Inferred
Major	49	49	239
Semi	22.8	22.8	78.3
Minor	4.7	4.7	17.3
Minimum samples	8	4	2
Maximum samples	16	16	16
Octant search	Yes	Yes	No
Minimum per octant	3	3	-

Examination of sections through the block model coloured according to grade estimates produced by the three methods showed small but important differences, particularly in the way higher grades follow the change in orientation of the orebody. This was very evident in the case of tetra modeling, less evident in the case of alternative local search regions, and not evident in the case of estimation domains and soft boundaries (Figure 6). Similar differences were observed in the produced kriging variance values with tetra modeling presenting lower variances and far more continuous compared to the other two methods (Figure 7). This suggests that grade estimates with tetra modeling can potentially have a higher confidence.

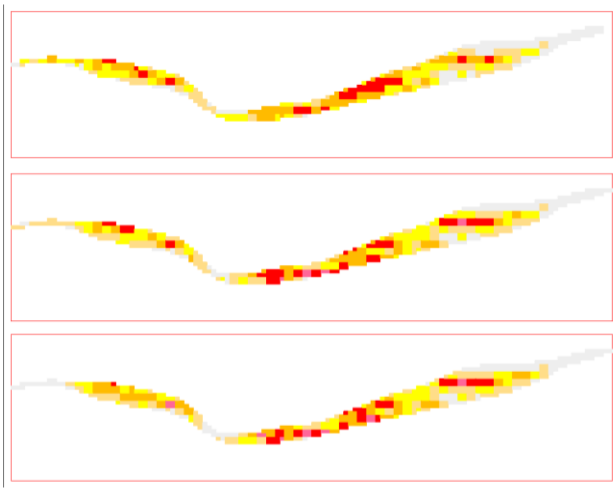

Figure 6: West-East cross-section through block model showing Cu estimates using tetra modelling (top), alternative local search regions (middle) and estimation domains (bottom).

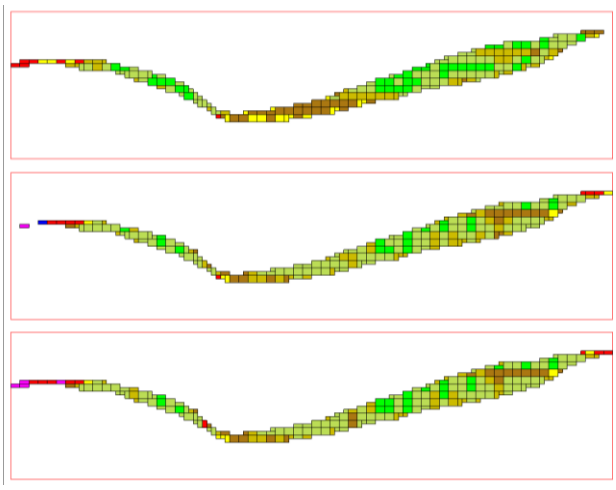

Figure 7: West-East cross-section through block model showing kriging variance using tetra modelling (top), alternative local search regions (middle) and estimation domains (bottom).

Average Cu grade and tonnage by resource class were calculated for each method. A cutoff value of 1% Cu was used to differentiate ore from waste. Table 3 summarises the results for the three resource categories and the three estimation methods.

Table 3: Resource estimation results according to method of treating deformities.

	Method	Blocks	Average %Cu	Tonnage
Measured (cutoff 1% Cu)	*Tetra Modelling*	8,168	1.571	6,442,520
	Alternative Local Search Regions	8,601	1.615	6,412,000
	Estimation Domains and Soft boundaries	8,499	1.624	6,408,920

	Method	Blocks	Average %Cu	Tonnage
Indicated (cutoff 1% Cu)	*Tetra Modelling*	464	1.575	134,400
	Alternative Local Search Regions	420	1.628	100,520
	Estimation Domains and Soft boundaries	492	1.571	106,960

	Method	Blocks	Average %Cu	Tonnage
Inferred (cutoff 1% Cu)	*Tetra Modelling*	482	1.262	63,840
	Alternative Local Search Regions	496	1.250	24,080
	Estimation Domains and Soft boundaries	534	1.329	5,320

	Method	Blocks	Average %Cu	Tonnage
Total (cutoff 1% Cu)	Tetra Modelling	9,114	1.568	6,640,760
	Alternative Local Search Regions	9,517	1.614	6,536,600
	Estimation Domains and Soft boundaries	9,525	1.623	6,521,200

The differences in the produced resource figures are more qualitative than quantitative. It seems that tetra modelling produces a slightly higher tonnage with a lower average grade, while the use of estimation domains produced the highest average grade with the lowest tonnage. It must be noted though that the classification was based purely on estimation run parameters (sample selection and search region) and not on any geostatistical level of confidence such as kriging variance. Implementing a different classification scheme that would utilise kriging variance can potentially change the resource table significantly, as the three methods produced quite different kriging variance values in the estimated blocks.

4. CONCLUSIONS

Three different methods of handling orebody deformities were deployed in the case study presented in this paper. The details of the underlying techniques and the application of each method to an undulating copper deposit were discussed. The examination of the results from each method proved that significant differences exist between the qualities and quantities produced. These differences become even more evident when a particular resource classification system and resources are reported in different categories.

In practical terms, the tetra modeling method was the quickest to setup but took the longest to run, while the use of estimation domains and soft boundaries took the longest to setup, but added no extra time cost during estimation as was the case with the alternative local search regions.

As a final conclusion, it is important for the resource estimation practitioner to fully understand the assumptions and implications of using a particular method for treating orebody deformities and a proper study to quantify the differences from using particular methods will be required in every case.

REFERENCES

Kapageridis, I. Use of Tetrahedral Modelling for Variography and Grade Estimation of a Structurally Deformed Phosphate Deposit. In: 11th International Congress for Mathematical Geology (IAMG'06 – Quantitative Geology from Multiple Sources), International Association for Mathematical Geology, Liege 2006.