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# Geological modelling of mineral deposits for prediction in mining

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**Abstract** Accurate prediction of the shape, location, size and properties of the solid rock materials to be extracted during mining is essential for reliable technical and financial planning. This is achieved through geological modelling of the three-dimensional (3D) shape and properties of the materials present in mineral deposits, and the presentation of results in a form which is accessible to mine planning engineers. In recent years the application of interactive graphics software, offering 3D database handling, modelling and visualisation, has greatly enhanced the options available for predicting the subsurface limits and characteristics of mineral deposits. A review of conventional 3D geological interpretation methods, and the model structures and modelling methods used in reserve estimation and mine planning software packages, illustrates the importance of such approaches in the modern mining industry. Despite the widespread introduction and acceptance of computer hardware and software in mining applications, in recent years, there has been little fundamental change in the way in which geology is used in orebody modelling for predictive purposes. Selected areas of current research, aimed at tackling issues such as the use of orientation data, quantification of morphological differences, incorporation of geological age relationships, multi-resolution models and the application of virtual reality hardware and software, are discussed.

**Key words** Orebody modelling · Reserve estimation · 3D GIS · 3D visualisation · Mine planning · Orientation data · Multi-resolution models · Morphological uncertainty · Virtual reality

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## Introduction

As in many other industries, the main concerns of the modern mining industry are with the source and cost of finance for developing new projects, as well as ensuring a profitable cash flow on existing operations. Meeting these concerns depends on successful technical and financial planning of mining projects. The fundamental starting point for such studies is to determine the characteristics of the mineral deposit to be exploited (Table 1).

Answering the questions given above requires the determination and interpretation of the characteristics of a mineral deposit in three dimensions. This involves the construction of a three-dimensional (3D) geological model which may consist of a mental image, drawings on paper plans and sections, or digital representations in a computer, or any combination of these. In all cases the final result is a geological model (often termed an orebody model) which represents the 3D spatial location of mineralised units and surrounding waste rocks, together with the 3D spatial variations in the physical and chemical properties of the different rock materials present.

As the main application of such models is the guidance of the design (type, size and location) of mine openings to be used during the exploitation of the mine, it is essential that the model is presented in a form which is meaningful to, and usable by, mine planning engineers. For instance, it is necessary to be able to quickly determine the dimensions and orientation of individual units, as well as obtaining estimates of the properties (e.g. volume, tonnage, average grades) of any planned mining volume within the deposit. Such knowledge can then be used to obtain estimates of capital and operating costs, together with the amount and quality of mineral production for given time periods, thus allowing the financial viability of different exploitation strategies to be assessed.

**Table 1** Critical questions to be addressed during evaluation of mineral deposits

| |
|---|
| Where is it? |
| How large is it? |
| What shape is it? |
| How deep? |
| How rich? |
| How dense (heavy) are the rocks? |
| How strong are the rocks? |
| How much is it worth? |
| How reliable are the predicted values? |

**Table 2** Data sources available for 3D geological modelling of mineral deposits

| |
|---|
| Direct sampling on surface (e.g. geological mapping, contact orientations, contact inter-relationships, physical sampling of pits and trenches) |
| Direct sampling of sub-surface (e.g. drill-hole core and chip samples, down-hole logging) |
| Indirect sampling of sub-surface (e.g. geophysical surveying including seismics, gravity, magnetics, electrical methods) |
| Genetic analogues (e.g. hydrothermal veins, volcanogenic massive sulphides, porphyry coppers) |

Conventional methods used for orebody modelling are reviewed before going on to consider the impact of computerised techniques in this field. Finally, selected areas of current research, which are aimed at improving the efficiency of computerised 3D geological modelling, are discussed.

## Geological modelling methods

### Data available

In the present context, a model is defined as a representation of reality, based on recorded measurements and/or other observations, which can be used to predict future measurements or observations. The type, accuracy and precision of the geological models created depend on the type and amount of data which are available for use in their construction (Table 2).

For the purposes of orebody modelling the critical parameters to be derived from such data are the location of boundaries between rock materials of widely differing properties, plus quantified measures of selected physical and chemical properties of the rock materials present. It is also essential that all observation or sampling points can be correctly located in three dimensions.

### Conventional interpretation methods

Conventional geological interpretation relies on the construction of plans and sections to represent the shape, size and properties of sub-surface materials within a mineral deposit (Popoff 1966). In the case of deposits which are exposed on surface, geological mapping based on observations of the distribution of different lithological units, contact relationships between different units and the orientation of boundary surfaces and internal fabrics, can be used to predict the likely disposition of such units in the sub-surface. Interpretations of such information, supplemented by indirect sampling using geophysical methods, allow the planning of direct sub-surface sampling programmes which normally provide the bulk of the data used for orebody modelling and reserve estimation. The interpretation of such information relies on three main approaches, namely, cross section based interpretations, contour plan based interpretations and analogies with other deposits of similar type (e.g. Annels 1991; Sides 1992a). The way in which such methods are incorporated in computer modelling systems is discussed below.

## 3D computer modelling for reserve estimation and mine planning

### Historical review

The evolution of computer applications in the mining industry is documented by the proceedings of the "Applications of Computers and Operations Research in the Mineral Industries" (APCOM) conferences which were initiated in 1961. With respect to geological modelling, most early work was concerned with database generation and management, often using large mainframe computers. The first attempts at computer modelling of sub-surface geology generally used conventional mathematical approaches such as trend surface fitting (e.g. James 1966), as was also the case with one of the earliest documented applications of 3D computer graphics (Kaas 1969). During the 1960s and 1970s several mining companies developed in-house programs for reserve modelling and mine planning on large open-pit operations (e.g. Fairfield and Leigh 1969), generally based on the use of 3D block model representations. In parallel with the development of computer hardware and software which made these applications possible came theoretical developments which saw the emergence of the field of geostatistics (Matheron 1963, Krige 1966 and David 1977). The 1970s and 1980s saw the widespread adoption of such techniques in computerised reserve estimation programs.

The trend towards high performance desktop computers, with good-quality colour graphics, available at relatively low costs, led in the 1980s to the emergence of a commercial market in geological modelling, reserve estimation and mine planning software. Most of the companies currently active in this area, such as Datamine International (MICL), Gemcom Services, Geostat Systems, KRJA Systems (Maptek), Lynx Geosystems (Geomin), and Surpac Software International, amongst others, were founded during the 1980s. The 1990s has seen a consolidation of developments in this field with continued improvements in the flexibility and ease of use of such software as well as the provision of enhancements such as 3D visualisation options. Reviews of the software currently available in this field are published periodically (e.g. Gibbs 1993), and an increasing amount of information on this subject is now available on the Internet (e.g. http://www.ned.dem.csiro.au/DEM/LEGACY/).

## Model representation

A variety of different methods are available for representing solid models in digital form on a computer, as summarised in Table 3. Such representation schemes are implemented using some form of data model, normally either a graph-based model or a Boolean model (Mortenson 1985). For 3D geological modelling applications, the storage of three principal types of data is required, namely geometric data (e.g. vertex coordinates), topological data (e.g. links between vertices used to define edges) and attribute data (e.g. grade estimates, densities, lithology codes, etc).

In terms of the application of such methods to geological modelling of mineral deposits, one can recognise two main groupings based on whether the principal interest of the user is in the shape(s) under consideration (geometry-based applications), or alternatively on properties which vary continuously through the volume of interest (volume-based applications). These two groupings correspond in a broad sense to vector-based and raster-based applications, respectively, in conventional geographic information systems (GIS; Bonham-Carter 1994).

Geometry-based applications concentrate on representing the sub-surface in terms of the boundaries between the main units present. Such applications rely mainly on boundary representation schemes, although sweep representations are also quite common (Table 3). In the case of boundary representations the geological shapes of interest are represented in the form of surfaces constructed from a series of "patches" which abut exactly along their edges. Tessellations, which rely on the use of planar facets, often appear rather jagged and artificial, and alternative approaches which define the patches on the basis of parametric functions are often adopted in order to obtain smoother, more natural looking, representations. Functions used include a variety of bicubic functions such as Coons = patches, Bézier surfaces and Hermite patches (Mortenson 1985), as well as non-uniform rational B-splines (Fisher and Wales 1992). These methods have in many cases been derived from techniques employed for modelling automobile and aircraft shapes in computer-aided design and manufacturing (CAD/CAM) software. Use of other representation types for geometry-based applications are less common, although there is some interest in the use of tetrahedral cell decompositions stored as simplicial networks (Pilouk 1996).

Volume-based applications concentrate on representing orebody properties which vary through space (e.g. density, grade, etc.). The most common approaches used in this instance are based on spatial occupancy enumeration (Table 3), whereby the volume of interest is represented by a set of regularly sized cells located in a fixed spatial grid. The cells used in this instance are termed voxels (volume elements), by analogy with pixels (picture elements) in two-dimensional systems. In a more general context the dimensions of such voxels can be different along each coordinate axis, resulting in a model based on equi-dimensional rectangular prisms. Such representations may require a large amount of data storage since the cell size is usually determined by the amount of detail required in areas where there is the greatest data density. Several methods have been developed to get around this problem by allowing for some degree of adaptability in the size of the volume primitives used. The gridded seam model, based on cells which are rectangular prisms with the same cross-sectional area but varying heights, is suitable for many coal deposits and hydrocarbon reservoirs which can be defined by a series of layers separated by sub-parallel surfaces. Another approach, the octree structure, an extension of the quadtree structure used in 2D systems, is based on a hierarchical decomposition of space into rectangular prisms (Bak and Mill 1989). The most adaptable type of volumetric model is a more general cell decomposition representation, whereby the volume primitives used may vary in size and spacing, as applied in many finite-element modelling systems. Where the properties of interest can be assumed to be constant over large volumes other representation schemes, such as sweep representations, may be used for volume-based applications. In such instances the properties of interest are assigned as attributes to the individual solid shapes stored.

## Modelling methods

The modelling methods used to create and edit 3D geological models have to allow for handling of the three sorts of data involved, namely geometric, topological and attribute data. In general, geometric and topological data are handled using methods which differ from those applied to attribute data. The most widely used modelling methods can be sub-divided into four categories, namely:

1. Modelling of geometry and topology using automatic boundary-fitting methods

**Table 3** Solid model representation schemes used for generating digital 3D geological models (types and description after Mortenson 1985)

| Type | Description | Usage in 3D geological modelling software |
|---|---|---|
| Sweep representations | Based on moving a point, curve, or surface (2D shape) along some path | This approach is easily implemented and is widely available since it is equivalent to manual methods whereby polygons (defined on sections or plans) are assigned a width, or thickness, of influence in order to represent orebody shapes as a set of polygonal prisms (e.g. serial slice and polygonal models) |
| Wireframe models | In this case, only the edges of an object are represented and this type is stored as a set of points, lines and curves | Although used in some systems to represent linked slice models, this type of representation contains insufficient information for unambiguously defining volume |
| Boundary representations (B-Reps) | Based on storing a set of faces (surface geometry), bounded by edges (curve geometry), which in turn are bounded by vertices (point geometry, i.e. co-ordinates). Where curved surfaces are approximated by planes and lines the term tessellated model is used | This is one of the most widely used approaches for representing the geometry of geological bodies. Several different approaches have been implemented in geological modelling packages, including:<br>– Triangular tessellations (often termed 3D triangulated irregular networks (3D TINs); These may either define open-ended surfaces or closed solids. Also referred to as simplicial tesselations)<br>– Polyhedral tessellations (e.g. linked-slice models derived from a series of polygons, or polylines, linked by quadrilaterals. Also referred to as complex tesselations)<br>– Piecewise parametric functions (e.g. NURBS) |
| Cell decompositions | Complex solids may be decomposed into a set of simple solid shapes (i.e. volume primitives), and can then be represented as the union of the set of cells into which they have been divided | Spatial occupancy enumeration schemes (see below) are widely used in geological modelling systems. Tetrahedral decompositions are also becoming increasingly important since this type of representation is common in many finite-element modelling packages |
| Spatial occupancy enumeration | This is special type of cell decomposition where the cells are cubical in shape and are located in a fixed spatial grid. (This definition is generalised here to include most 2D or 3D grid-based schemes which can be either linear or hierarchical in structure) | This is the most common type of representation used for storing models of property (e.g. grade) variations in mineral deposits. Several different approaches are used, including:<br>– Regular 3D block models (also termed voxel models)<br>– Gridded-seam (rectangular prisms with variable height)<br>– Octree (recursive sub-division)<br>– Adaptive block models (e.g. regular and gridded-seam models where sub-blocking is allowed; termed geo-cellular model in the latter instance) |
| Constructive solid geometries (CSG) | Described in terms of elementary shapes (half spaces) or primitives (bounded primitive solids), which are combined using a binary tree of set or Boolean operations in order to represent complex solids | General not much used for geological modelling, although approach is common in CAD/CAM software used for applications such as modelling of automobile parts |
| Instances and parameterised shapes | Used in cases where new shapes are derived by simple linear transformations of existing shapes | Usage for geological modelling is rare; however, this approach can be used for simple models based on genetic concepts (e.g. elliptical fault planes, lenticular sulphide orebodies) |
| Hybrid schemes | Combinations, or adaptations, of the schemes given above | Representation types used in several reserve modelling software packages fall into this category, including:<br>– Boolean combinations of boundary representations<br>– Complex polyhedra (e.g. some forms of linked-slice model)<br>– Polytrees (boundary representations where vertices are stored in an octree-type structure) |

2. Modelling of geometry and topology using manual boundary-fitting methods
3. Modelling of attributes using non-geostatistical 3D interpolation methods
4. Modelling of attributes using geostatistical 3D interpolation methods

These four categories of modelling methods are discussed separately below.

Automatic boundary fitting methods include techniques such as triangulation and contouring, which have traditionally been used for manual estimation of reserves (Popoff 1966; Annels 1991). A variety of different triangulation algorithms are available for use with irregularly distributed data points which define surfaces that have relatively simple geometries (i.e. no repetitions in the Z direction at any given point). Such algorithms usually generate the most equiangular triangulation possible in the plane of interest, termed a Delaunay triangulation (Watson 1992). Editing of the resultant models is possible by adding, deleting or relocating vertices and then retriangulating. Constraints may be imposed during triangulation so as to preserve digitised contour lines, crest lines or river valleys (Pilouk 1996). A polygonal tessellation based on connecting the circumcentres of Delaunay triangles, termed a Voronoi tessellation, has the property that it defines the nearest neighbour polygons for the set of vertices (Fig. 1). By weighting the thicknesses, or other property values, at each vertex according to the area of the corresponding polygon, estimates of volumes and tonnages can be made. This approach is equivalent to the conventional polygonal method of reserve estimation.

For models based on curved patches, defined by parametric functions, more complex surface fitting procedures may have to be followed. The resultant models are still dependent on the raw data points, plus optional additional control points, which can be modified by the user. Selection of the final model may be based on some mathematical measure of degree of fit to the original data points, supported by visual comparisons. An interesting development in this area is the discrete smooth interpolation (DSI) method developed by Mallett (1992) which forms the basis for 3D model building in the GOCAD program. In this instance the fitting algorithm is optimised to produce a result in which a local "roughness" criterion is minimised.

Automatic surface fitting can also be based on contouring of a set of Z-values in an $X$–$Y$ plane. A wide range of techniques have been developed in conventional contouring packages for applying this procedure. One group of contouring methods relies on extracting contours from triangles created using automatic triangulation algorithms such as those discussed above. Another group of contouring methods relies on extracting isolines from a regular 2D grid of interpolated values. The interpolation procedures used in such cases are similar to those described below under 3D interpolation methods.

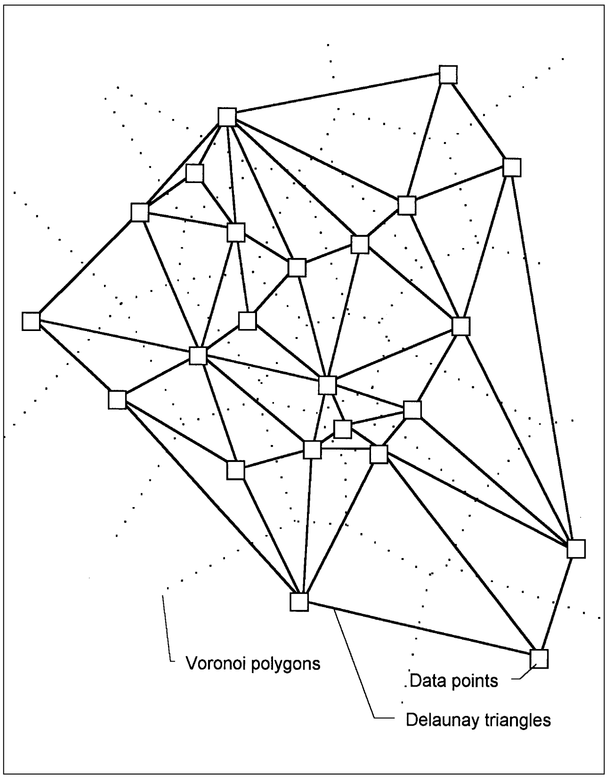


**Fig. 1** Delaunay triangulation showing complementary Voronoi polygons

Manual boundary fitting methods generally rely on the use of geological interpretations based on a series of parallel plans or cross sections. The simplest approach is to digitise polygonal shapes (defining the outlines of different geological units on each plane) and to then assign these a width of influence half way to the neighbouring planes on either side in order to create a sweep representation (Fig. 2). This method, often termed the serial-slice approach, has the disadvantage that abrupt changes in shape may occur across the boundary planes defining the limits of influence of adjoining slices (or interpretation planes). To overcome this problem a modified approach, termed the linked-slice method (Fig. 2), is often adopted whereby the polygonal shapes, or polylines representing individual boundaries, are directly connected by a series of lines (which form triangles or quadrilaterals) in order to form more complex shapes which vary gradually from slice to slice (e.g. Houlding 1994). Many of the algorithms used for creating such boundary representations have been adapted from ones developed, in the field of medical imaging, for use in constructing 3D models of the human body (e.g Keppel 1975). Some systems allow for the use of 3D polylines in the linked slice approach, such that drill-hole intersection points lying some distance away from the interpretation plane can be incorporated into the digitised shapes. Although the spacing between interpretation slices may be variable

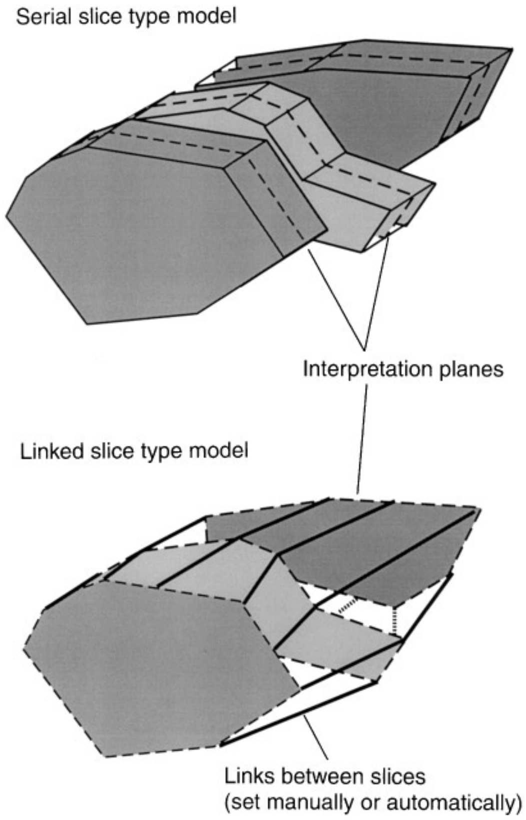


**Fig. 2** Slice-based modelling methods, showing serial-slice (sectional) approach and linked-slice approach

in both the serial-slice and linked-slice methods, in general all interpretation planes are parallel in order to ensure that no gaps or overlaps occur. When the linked-slice method is used, problems of gaps and overlaps may also arise in the volumes lying between the interpretation planes particularly in cases where the boundaries between adjoining units have to be linked together more than once.

A 3D interpolation using non-geostatistical methods includes the use of a wide variety of spatial interpolation procedures which can be used to estimate values for a series of closely spaced points (representing the centres of, or a series of points within, the volume primitives being used) based on a series of measurements at more widely spaced sampling points. Interpolation methods rely on choosing one or more of the surrounding data points and calculating an estimate based on a combination of the measurements at these points. The simplest case, using only one data point (the nearest neighbour), is comparable to the polygonal method applied in manual reserve estimates. Simple moving average interpolation is based on the use of more than one sample, but with equal weights being assigned to all the samples used. Inverse power of distance weighting methods (IPDW) are based on assigning greater weights to samples which fall closer to the point to be estimated (Davis 1986). When using such methods, and also those based on geostatistical approaches, careful attention must be paid to the parameters used in selecting samples (e.g. search prism or ellipsoid size and orientation, use of anisotropic weighting functions, minimum and maximum number of samples to be used, etc.), since these have a significant impact on the estimates obtained (Isaaks and Srivastava 1989).

A 3D interpolation using geostatistical methods is one of the most widely used approaches to interpolation in computer-based reserve estimation. Such methods fall under the general term kriging, named after D. Krige whose early work on the South African gold mines formed the foundation for this approach (Krige 1966). Much of the early theoretical foundation for this field was developed in France (e.g. Matheron 1963), although workers at many centres around the world have contributed to recent advances in this field. One of the major advantages of using kriging, as opposed to non-geostatistical methods, is that it provides a prediction of the estimation uncertainty (the kriging variance). A detailed discussion of geostatistical interpolation methods is beyond the scope of this paper, and readers are referred to standard textbooks (e.g. Isaaks and Srivastava 1989). The proceedings of several recent international conferences on geostatistics provide details of current research in this field (Dimitrakopoulos 1994; Soares 1993).

## Visualisation

An essential element of 3D modelling systems is the ability to view the geological models and stored geological data. In the first instance, such visualisations are used during the creation and verification of 3D geological models in order to ensure that these are realistic, and that there are no gross discrepancies when they are compared with the data from which they are derived. Secondly, such displays provide the means by which planning engineers can be guided in the design of mine openings and production sequences. The display techniques most commonly used are 2D representations on plans or sections, and rendered 3D visualisations. The information displayed is normally represented by points, lines, areas and text. A wide number of display attributes (e.g. colour, line type, size, symbols, shading, etc.) can be varied in order to combine a large range of information in a single image (e.g. Keller and Keller 1992). Further processing is often necessary during, or prior to, the generation of such displays, including planar sectioning and projection, conversion between geometric and volumetric representations, and surface and volume rendering.

Planar sectioning involves the calculation of the intersection of a 3D model with a plane at any orientation. The methods applied for calculating the intersection lines and areas required include a range of techniques which have been developed for 2D contouring. In contouring programs the generation of contours is usually intimately linked to the generation of a surface representation in vector or grid form (Watson 1992). The modelling and interpolation methods used include the surface fitting and interpolation approaches discussed previously, with contour lines being derived from the intersections between a series of iso-value planes and the geometric primitives (e.g. triangles or cubes) which represent the 3D geological model. Planar projection involves projecting data which are distributed irregularly in 3D space onto a single plane, and is commonly used when displaying drill hole or sample data which are not co-planar with the plane of interest. In such instances it is necessary to specify a maximum projection distance, on either side of the display plane, when selecting the data to be displayed, Planar projection is also involved when a topographic surface is represented as a series of iso-lines for different projection distances from the display plane.

Before 3D visualisation techniques can be applied, it is often necessary to convert 3D models from one representation type to another, depending on the requirements of the visualisation software used. The conversion of an attribute model stored as a cell decomposition representation into a boundary representation involves 3D iso-surface extraction. Procedures used for the extraction of such iso-surfaces from a 3D grid are analogous to those used for the extraction of an iso-line from a 2D grid. An implementation of this approach is illustrated in the Interactive Volume Modelling (IVM) program of Dynamic Graphics (Belcher and Paradis 1992). Conversion of a geometry model stored as a boundary, or other type of, representation into an attribute model with a higher resolution (sometimes referred to as voxelization) involves testing the relationship of the volume primitives in a voxel model with the elements of the geometry model. This requires tests to determine whether the centre of each voxel is within a given solid shape, or on a specified side of a surface, and is often carried out using a scan-line conversion procedure. The manipulation of models during 3D visualisation is usually based on cubic voxels which may often be smaller than the smallest cells used in the original model. In many cases additional processing of stored spatial occupancy enumeration representations, involving sub-division of the cells, is necessary in order to convert them into voxel models suitable for 3D visualisation purposes.

Enhanced visualisation involves rendering of 3D digital representations to give the impression of a 3D image when displayed as 2D pixels on a computer screen (Kaufman 1991). Techniques have been developed for volume and surface rendering which take into account the relative positions of the object(s) being viewed, the viewer, and the light source(s) (Nielsen and Shriver 1990). These operations involve calculation of perspective, removal of hidden lines and surfaces, shadow casting, colour mapping and shading of surfaces, based on methods such as ray tracing and z-buffering. Additional realism can be added to the final images by allowing for variations in transparency and reflectivity, and the use of texture mapping rather than simple colours. Virtual reality applications require high-speed calculation and display of stereo-pair images based on similar procedures.

## Application

Besides providing facilities for data capture and model building, computer programs used in an applied field must provide output in a form which is meaningful for, and useful to, the end users. In the case of mine planning and reserve estimation graphic displays of information are required, both as interactive displays and also as scaled plans and sections for manual design work. It is also essential that such models can be interrogated in a manner which allows the calculation of volumes, tonnages, and average grades, within planned mining volumes defined by the user.

The design of mining volumes often uses similar approaches to the model building procedures described previously, in particular the slice-based methods whereby mining volumes are defined by polygonal outlines (digitised on a plan or section) with fixed heights or thicknesses. Design of such volumes is supported by application programs through the display of geological units and grade variations while interactive editing of mining shapes is performed (Fig. 3). Evaluation of designed mining volumes should allow the generation of output listings or of files containing volumes, tonnages, and grades for a range of metals, derived by interrogation of the 3D models. Another important aspect of such work is that it should be possible to assign each design volume to a given time period so as to allow production schedules to be generated and evaluated. Such information allows for rapid assessment of alternative technical and financial options for exploiting a mineral deposit, thus facilitating greater planning efficiency.

Computer-based mine planning systems offer a considerable number of advantages over manual methods, in particular the fact that new information can be incorporated and models updated very quickly. Also, a wide range of metal grades or other properties of interest can be considered simultaneously during mine design and production scheduling, and information can be retrieved and displayed at any scale very rapidly. In addition, some tools, such as interactive 3D visualisation and geostatistical interpolation, are generally not practicable without the use of computers. The ability to rapidly update models, and to create models at different resolution levels, are important factors in allowing efficient and timely planning of exploitation strategies (e.g. Richards and Sides 1991).

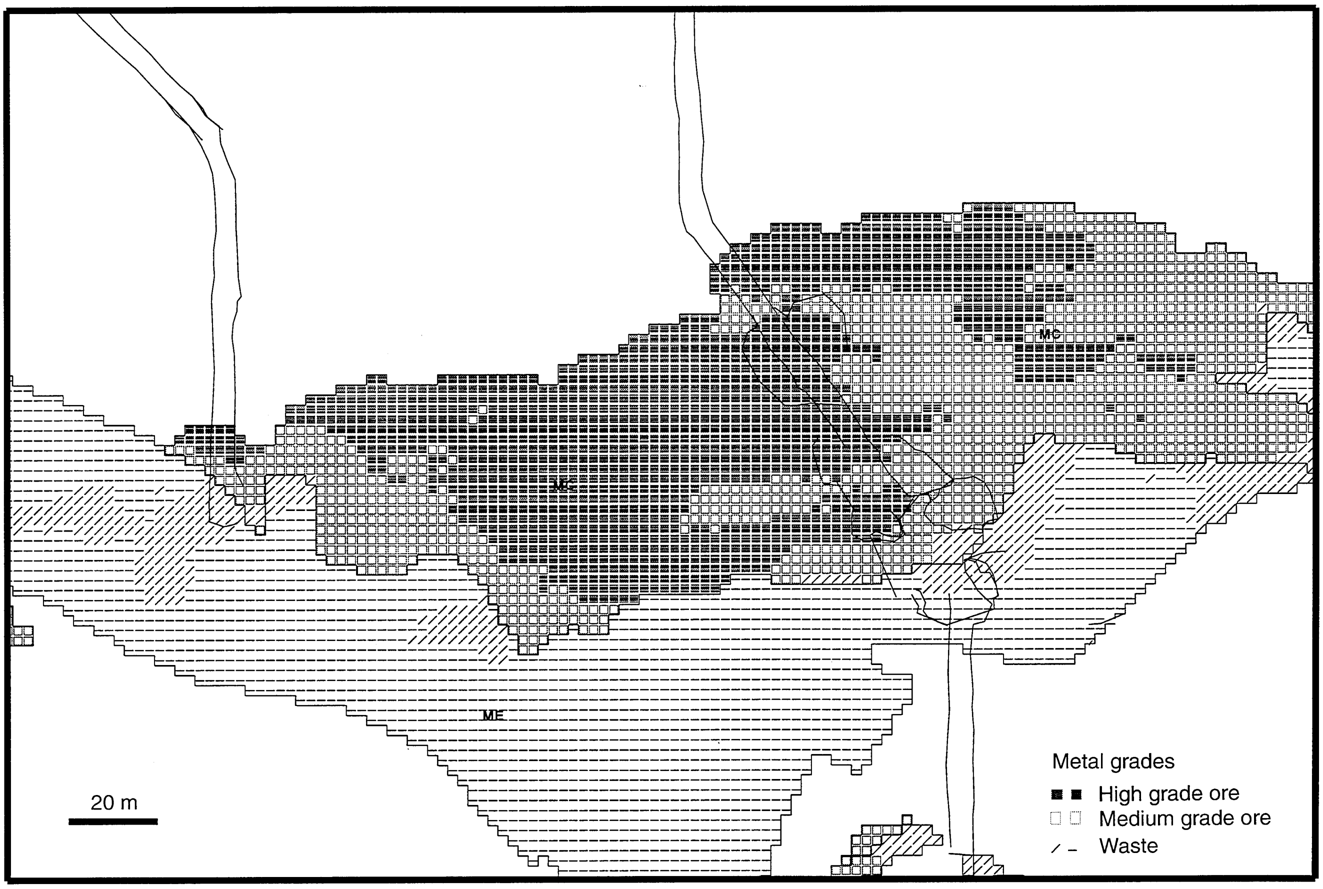


**Fig. 3** Example of a 2D graphic display showing block model contacts and grades and surveyed mine openings

## Research topics

### Introduction

The success of commercial 3D modelling systems, used for geological modelling and reserve estimation, is illustrated by their widespread acceptance in the mining industry. Whereas previously most large mines tended to develop their own in-house systems, the use of commercially available systems is of increasing importance. Nevertheless, customising of commercial packages for use at individual mine sites may still be necessary in some instances. Despite the advances in recent years there is still a need for constant development of such systems in order to ensure continued improvements in ease of use, functionality, and the accuracy and precision of the results obtained. A selection of current and future research topics aimed at dealing with some of these problems are discussed below.

### Use of orientation data

Field geological mapping relies heavily on observations of the orientation of contacts between different units as well as the orientation of internal fabrics within different units. Such data can be used to determine the relative ages of different units (on the basis of cross-cutting relationships) as well as allowing the extrapolation of surface measurements laterally or vertically downwards. Little direct use of such information has been made in 3D modelling systems to date, although methods exist for treating such information statistically (Swan and Sandilands 1995) and geostatistically (Young 1987).

Recent work has illustrated how the interpolation of observed and interpreted orientation data can be used to construct a volume representation of the internal fabric of a deposit (Sides and da Silva 1994). Figure 4 shows a set of vectors, representing variations in the orientation of a stratabound deposit, which are stored in a regular block model and were derived by interpolation from a set of scattered observation points. In this instance the interpolated orientation values were used to control the orientation of the search prism and anisotropy ellipsoids during interpolation of ore grades, resulting in more realistic estimations in areas of rapid variations in strike and dip of the ore horizon.

Further research and development along these lines should facilitate the extraction of orientation data from

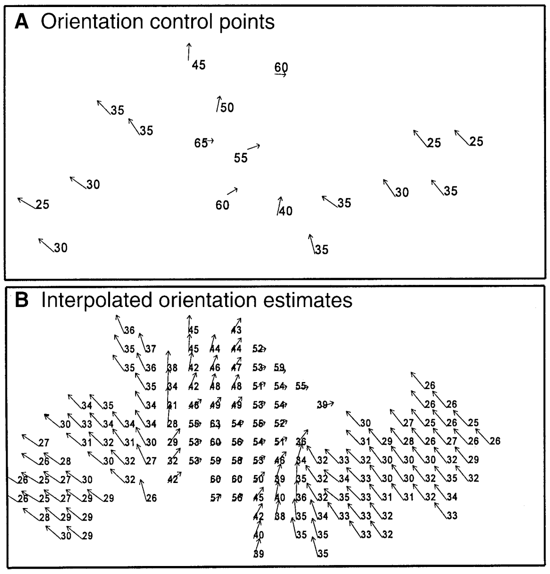


**Fig. 4** Plans showing **A** orientation data points and **B** interpolated orientation estimates based on these data

bounding surfaces stored as geometric representations, and their subsequent application in generating volumetric models of internal fabrics of different units. Additional work is currently being carried out on the use of such "fabric" models to improve the estimation of internal properties in situations where only sparse data measurements are available (B. Orlić, in preparation).

## Quantification of morphological uncertainty

Given the increasing use of 3D modelling systems it is now quite frequent to have several alternative models for the same deposit. This situation commonly arises during the evolution of a project from exploration, through evaluation, to the exploitation stage (e.g. Richards and Sides 1991). Such a sequence of models reflects an increasing density of raw data, and greater precision in the resultant models, as parts of a deposit fall within a gradually shortening planning time frame. Ultimately, there are also separate models which reflect the situation actually encountered during mining, and these are often used to derive empirical measures of the quality of the reserve models on which planning was based. In ideal cases the global predictions of models made at all stages of a project would be similar (i.e. no overall bias should be present if the sampling and modelling strategies used are appropriate), although there will be differences in detail reflecting the greater precision (model resolution) possible as more data are collected. Quantification of these local differences is essential in order to establish measures of the predictive success of modelling done using different amounts of data and/or different modelling strategies.

Much work has already been done in developing geostatistical approaches for the calculation of estimation uncertainties based on the patterns of spatial variation of the data (e.g. Isaaks and Srivastava 1989). An area which has received less attention is that of quantifying geometric differences between different models (e.g. Houlding 1992). Sides (1994) presented an approach to this problem based on studying the statistical variations of a regular set of sampling rays which are intersected with two alternative geometric models is order to obtain a measure of the variation in locational accuracy of predicted contact positions.

Based on this work, experiments are being carried out on the application of a simple 3D filter to regular block models in order to quantify the variability of 3D shapes. The objective of such tests is to obtain numerical measures of morphological uncertainty which can be represented graphically, and analysed numerically, during mine planning and design work. The basis of the approach used is a filter (Table 4) which establishes a measure of similarity between each block in a regular block model and its immediate neighbours. This is an empirical approach based on the premise that most block model codes are assigned using a simple point-in-polygon (or more correctly point-in-polyhedron) test. As a consequence the contact position represented in a block model may actually fall anywhere between a given block centre and the centre of one of its neighbours. The weightings applied in the filter are based on the amount of overlap obtained if the central block is shifted half a block dimension along one or more of the principal axes of the block model. For neighbouring blocks which share a common face an overlap of 50% is obtained, whereas for those sharing a common edge it is 25%, and for those sharing a common vertex it is 12.5%, hence giving weights of 4, 2 and 1, respectively (Table 4).

This filter can be applied to block models of orebody parameters, such as particular lithological units, or zones above a selected cut-off, in order to obtain some measure of the overall confidence of the value assigned to a particular block. A block totally surrounded by

**Table 4** Procedure used to calculate an empirical measure of morphological uncertainty for a regular block model

Weights are accumulated on the following basis where surrounding blocks have the same code as the block being considered:

Slices above and below

1 2 1
2 4 2
1 2 1

Slice containing block of interest

2 4 2
4 0 4
2 4 2

The morphological uncertainty measure (MUM) is then calculated:
MUM (%) = (sum of weights/56)*100

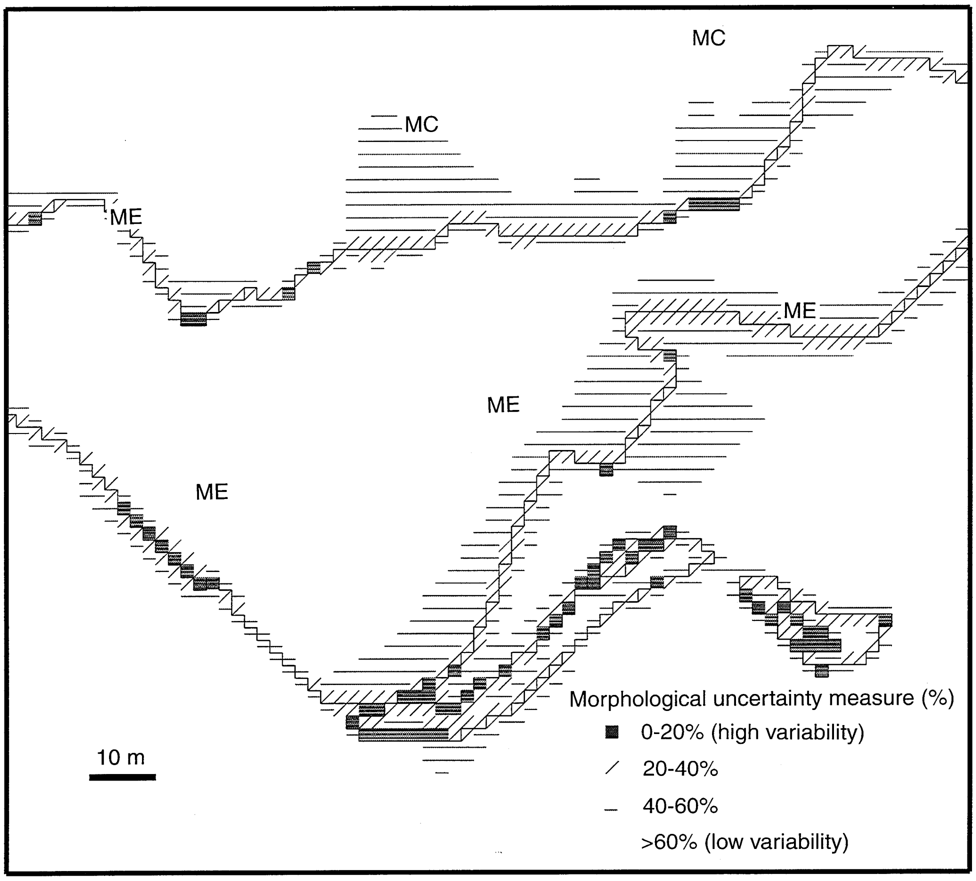


**Fig. 5** Plan showing block values for a morphological uncertainty measure (as explained in text). Low values highlight areas where the orebody is thin (e.g. bottom right), and also areas of flat-lying contacts (upper centre and right of centre)

blocks which fall within the same zone will receive a value of 100%, whereas one surrounded entirely by blocks from different zones will receive a value of 0%. By displaying this parameter on a standard section or plan the user immediately has some idea of the confidence which should be placed in different parts of the model, as illustrated by the example presented in Fig. 5.

Likewise the measure of uncertainty obtained can be handled in the same manner as ore grades during standard mine planning estimation runs in order to assess the relative confidence which can be placed on individual mining volumes. Schedules can then be optimised to ensure that this measure of uncertainty does not vary drastically over time.

## Incorporating geological time

The concept of geological time was one of the most important concepts which led to the development of geology as a separate science (Gould 1988). Field geological mapping still concentrates on the use of contact relationships between different units to determine their relative ages, and hence to unravel the geological history of an area. Such relationships usually form a key element in the preparation of geological maps and sections for 3D modelling of mineral deposits; however, they are rarely explicitly stored in the resultant digital models.

Incorporating geological time into such models requires the addition of a time sequence for the stored volumes and/or boundaries. This approach is illustrated by an educational program, GLG-MAP, used for instruction in geological map interpretation (C.E. Ford, unpublished data). This program allows the definition of a series of structural blocks with a defined order of priority which controls the contact relationships between them (Fig. 6). A similar hierarchical ordering of model elements was also used by Sides (1992a, b) in order to control the intersection relationships between different geological boundaries.

## Multi-resolution models

As noted above, a range of models of increasing resolution are normally developed between the initial discovery of a mineral deposit and its eventual exploitation. As the time of exploitation draws closer, more information becomes available from surrounding areas thus allowing the level of detail (resolution) of the model to be increased in order to support planning on shorter time frames. For instance, during initial project feasibility studies a planning time frame of 2–5 years

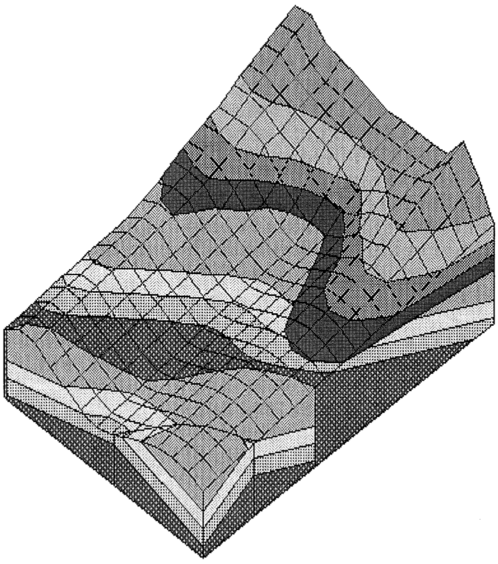

**Fig. 6** Block diagram illustrating the use of a hierarchical ordering of structural blocks to control contact relationships (generated by the GLGMap program)

may be adequate; however in an operating mine production is normally planned on at least a quarterly or monthly basis.

These requirements result in a need for models with variable levels of resolution. This need is fulfilled in several systems by the use of adaptive data structures such as triangulated surfaces and sub-blocking. Nevertheless, it is usually quite cumbersome to use the same model for both short- and long-range planning, and this topic merits further investigation. Approaches developed for handling multi-resolution digital terrain models (De Floriani and Marzano 1994) may prove useful in this regard. Advances in this area are likely to improve the applicability of 3D modelling systems for regional-scale geological studies, where detailed information in the vertical direction is very limited.

### Application of virtual reality techniques

Virtual reality is a field of rapid current developments in hardware and software which offers considerable potential for applications in 3D geological modelling. Such systems offer enhanced visualisation and easier interaction during the creation and application of 3D models. Some research has already been initiated in this area with respect to modelling the usage of equipment in mining operations (Schofield et al. 1994), and it is likely that such techniques will be applied to mineral deposit modelling in the near future.

Another aspect of interest is the development of new interfaces, such as head-mounted stereo displays, data gloves and virtual workbenches (Krüger et al. 1995). These technologies offer the possibility for a group of users to jointly interact with 3D digital models which could facilitate communication between geologists, planning engineers, management, government officials and the general public. The concept of augmented reality, whereby a digital image is superimposed on the real world vision of a user, is also of interest. With the reduction in size and increased portability of many computing and communication devices, it is possible that in the future users could view and edit 3D models directly in the field.

## Conclusions

The overall success of geological predictions in mining is illustrated by the fact that large mining companies regularly borrow millions of dollars of capital in order to develop or expand mining operations based on such predictions. Banks and other financial institutions would be unlikely to continue lending such money if they were not confident of success in the majority of cases.

The role of computer modelling in increasing the speed and efficiency of such predictions is evidenced by the competitive market in specialist mining software which has developed over the past two decades. Despite the power of the systems currently available, there is a need for continual research and development in order to improve their flexibility and ease of use, as well as taking advantage of new developments in computer hardware and software.

Such improvements should allow for more accurate, precise and timely geological predictions, thus facilitating optimum technical and financial planning of the exploitation of mineral deposits. In many cases this will serve to extend the world's exploitable resource base, since inaccurate models often lead to sterilisation of reserves or loss of ore grade material which is incorrectly mined as waste.

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