Introduction

Software technology is developing rapidly, changing the way we can utilise geoscience datasets. A major change has been the advent of new quantitative structural modelling in place of traditional sectional interpretations. Technology now offers the ability to host numerous datasets and facilitates easy integration for analysis, research and understanding relationships between multi-disciplinary data.

A broad aim for achieving value added insight is through the construction of a structural model. This is defined as a 3D volumetric model containing the family of faults and contacts, and their topological relationships, which together define geologically meaningful sub-volumes within the earth model.

There are various quantitative methods of data integration and model construction. The GOCAD software technology has several aspects which move beyond CAD based methods of interpreting observation geological and structural datasets. This 3D interpretation and modelling is done at various scales from an outcrop, camp, or ‘terrane’. Interpretation of structural and geological setting is then facilitated either through structural field interpolation, CAD based wireframing methods or implicit mathematical wireframing technology.

As an input to and feedback mechanism to modelling, GOCAD can test the 3D models against observed potential field data, and either update the geometry of the models or provide information on the data misfit.

The aim of the data integration, value added insight and the construction of a structural model is to improve the decision making process with more successful outcomes. Outlined below are the basic requirements for the business of mining and/or mineral exploration. This is followed by addressing how technology is meeting these requirements.

The Business Requirements of a Useful Structural Model

For software technology to be a powerful addition to the exploration process it needs to provide first class 3D visualisation but more than this it needs to be able to construct a topological structural model in a timely fashion. The resultant model should be readily convertible from its vector (surface boundary format) to a raster/gridded model and both the vector model and the raster model should support any number of properties.

A structural model which is useful for making business decisions either within mine or in mineral exploration must host current observational data. The requirement is therefore that a model can be quickly constructed initially, but also the model must be easily updateable when new data is provided. As will be discussed in the next section, this fundamentally means that model editing should not just rely upon CAD based construction from section interpretations. Editing needs to be applied directly in 3D space.

A structural model can be utilised by engineers, geochemists, geophysicists, resource geologists, project geologists and anyone needing to make decisions based around 3D datasets. The model, in either vector or raster format, therefore needs to be easily connected to value-added processes such as geophysical forward modelling and inversion, geochemical data query and analysis, as examples. In addition, the model should facilitate business value-added analysis such as exploration targeting or geotechnical hazard evaluation.

While some requirements between mine and exploration applications may be common, there is always a need to customise analysis techniques allowing for free form data interrogation to draw out conclusions for specific project needs. Analysis tools need to be flexible to allow this.

The Technology Eco-system for Structural Modelling

To meet the business requirements of a structural model, it becomes evident that a powerful visualisation, modelling and quantitative 3D software technology is required. A “technology eco-system” based on GOCAD meets these requirements by combining the availability of CAD style modelling with the DSI-based approach to structural data (“Discrete Smooth Interpolation”—a powerful approach to fitting natural surfaces to constraining data—Mallet, 1992),
as well as its integration with SKUA implicit modelling (Mallet, 2004), SPARSE for parametric construction of regional structures from limited data (de Kemp and Sprague, 2003; Sprague and de Kemp, 2005) and 3D GIS capacity to interrogate, explore and analyse the model (Sprague et al., 2006). In addition GOCAD facilitates the communication of a model with potential fields or electrical geophysical datasets to either test the model integrity through forward modelling or update its geometry or rock property values through inversion (McGaughey, 2007).

**Software Space to Integrate all Data**

Visualisation must be able to incorporate observation geological data along with a DEM, geology maps, geological models and drill holes, stereonets and other standard plots. This common space for visualisation provides the opportunity for maximising the use of all data for understanding relationships amongst the multi-disciplinary datasets for either geological modelling or orebody research. In addition, value added insight as results from queries and additional properties can be hosted in the same quantitative 3D environment. An example of this is shown in Figure 1, where a particular structural population is identified in the stereonet, and directly linked back to the 3D visualiser to make inferences on whether spatial clustering can help with interpreting the structural model.

The querying and visualization processes combine to form a software technology system that is a truly collaborative environment. The ability to draw qualitative and/or quantitative conclusions using multi-disciplinary data, combined with 3D GIS query capacity, is a direct consequence of the technology environment. The aim of this is to add value to all of the data being collected, and thereby critically support business decisions with a fact-based, collaboratively interpreted model (McGaughey, 2006). This is in contrast to databases that purely host data, or separate packages being used for singular data source interpretations, which provide unconnected findings on which to base decisions or conclusions.

**Structural Model Construction**

The final aim of interpretations based upon integrated and quantitative analysis of geological and structural observations is the construction of a structural and geological model that will support business decisions. If a traditional approach to produce this is adopted then multiple sections must be constructed along the entire project area. These can create bias, are tedious to produce and can be erroneous in areas with limited data. Instead new technologies such as SKUA implicit modelling, can actually utilise the observation data and any subsequent local interpretations as inputs to build a structural and faulted geology model without a need for systematic sectional interpretation.

To move from observation to interpretation, datasets which are generally available include:

- geology fact and interpretation maps
- 2D seismic, magnetotelluric and gravity profiles, and associated geological interpretations
- potential fields grids and images
- field structural measurements.

**Preliminary Interpretations and DSI**

To build a geological and structural interpretation from observation data, classically sections are interpreted to start the construction process. An example of this is from the Queensland Geological Survey Mt Dore interpretation as shown in Figure 2. Seven sections are interpreted with stratigraphy and faults. Data that is used to construct sections includes geology maps, structural measurements, gravity, magnetic, magnetotelluric, and seismic profiles.

The sections (Figure 2A) rely upon the geology map, field structural measurements and potential fields data for construction and validation. The sections are then integrated with geology map contacts and additional interpretations such as fold hinges (Figure 2B).

Advantages to the use of selected sections are that you are already performing validation on the model in 2D before construction of a 3D model. The disadvantage is time, and relevance with the advent of rapid modelling technology directly modelling in 3D.

In addition to sections, or as a separate option to initiating the construction method, the GOCAD Discrete Smooth Interpolation (DSI) algorithm can be utilised to directly model a fault plane or geological contact in 3D space.
without the need for any section interpretations. This same algorithm when creating geometry makes use of the location of a contact point but can also use the orientation of that contact point to guide the geometry of the surface.

Potential Fields to Model Contact Orientations

Modelling can be commenced by using potential fields data for dip modelling along contacts. If a geological boundary provides a density or susceptibility contrast which is evident as a lineament in potential fields data, then 3D potential fields modelling either through forward modelling or inversion will provide information on the dip of the contact. If a contact is fault bounded the result provides information on the orientation and dip of the fault. The contact can be stratigraphic, e.g. the conformable contact between mafic and felsic volcanics. In this instance the orientation is providing dip information on the entire stratigraphic sequence. Dip modelling of a geological unit is shown in Figure 3. In this case three proposed models are forward modeled and the response compared with the observed TMI. A dip of 70 degrees provides the best match and this dip value is then assigned to the contact line for structural modelling. This provides early feedback on the validity of the structural model interpretation; ensuring basic geometries are correct before undertaking complete 3D model construction.

Structural Field Interpolator and Sparse Grip Frames

The 3D Structural Field Interpolator allows computing of 3D plunge and structural field models from raw orientation data (Figure 4). This interpolation technique can provide structural guidance when interpreting geology in 2D as well as 3D. In addition to being an input to SPARSE grip frames, DSI, or SKUA contact modelling, the structural orientations can act as constraints for potential fields geophysical inversion.

Curves and 3D raster grids can be an output describing the geometric behaviour of planar features in the volume being modelled. The output models for plunge characterise the geometric behaviour of the plunge field in the volume being modelled.

SPARSE ribbons or numeric dip values along geological contact curves can also be utilised where stratigraphic relationships are combined with known unit thicknesses. Simple geometric rules can then be applied to convert
apparent and absolute unit thickness to a unit dip along the contact. Although this is simple in concept it relies upon many 3D GIS tools, property manipulation and transfer between objects. This analysis is easily performed in the GOCAD quantitative 3D environment.

Implicit Modelling with SKUA

Implicit modelling provides a means to rapidly construct and update structural models from observational and interpretational data, as well as a set of structural and stratigraphic relationship rules.

The SKUA implicit modelling engine makes use of point sets, representing structural and geological contacts, as well as numeric orientation information. The structural measurements are either defined on contacts or can be ‘inter unit’. Curves are used to define map traces of faults and geological contacts, as well as interpretations on section. They are also used for any grip frames or fold hinges resulting from analysis of structural data or tools within SPARSE. Surface wireframes can also be utilised as inputs and act to guide geometry of all conformable boundaries.

The first stage of modelling within SKUA is creation of a water-tight fault network, as shown in Figure 2C, followed by faulted stratigraphic contacts (Figure 2D). The mathematical nature of modelling a complete stratigraphic package in one step ensures that geometries guided by interpretation and observation on any contact are adhered to by neighbouring contacts which may have no data. This ensures very rigorous QA/QC of the input data and also maximises the use of the all observation data to inform all areas of the volume being modelled. SKUA provides the added addition of creation of a volumetrically and geometrically correct raster representation of the model. This has many benefits over standard raster models which rely upon rectangular cells of equal or varying size.

Testing Models Against Observation Data - The Opportunity of Quantitative Modelling with Potential Fields Data

Geophysical data can be an important component to the initial construction of structural models. Once a model is constructed, modern inversion algorithms such as VPmg (Fullagar et al., 2006) can either update the geology model directly (to reduce misfit between computed and observed magnetic and gravity datasets) or change the density and susceptibility rock property values assigned within the structural model. The former is known as geometry inversion, the latter heterogeneous inversion.

Geologically constrained geophysical inversion relies upon a structural model as well as rock property information. Rock property information is key to relating the structural model to geophysical data. Once the structural model is fully compliant with observational geology data such as mapping and structural measurements, misfit with potential fields data is due either to errors in the geometry of the model or the rock property distributions within units. Therefore, an iterative process of updating geometry and heterogeneity of units is the most common process for ‘real world’ projects. An outcome of this is that heterogeneity within units, demanded by the geophysical data, can often lead directly to additional insight in metamorphic or alteration variations (figure 5). These variations are often used for identification of mineral exploration targets.

When inversion is performed within a package such as GOCAD, constraints can be assigned so that the geometry of a particular geological boundary or unit rock property can be fixed by observation and interpretation data where it exists, but inversion may change the boundary/rock property away from these data.
Conclusions

3D structural models sit at the heart of our capability to make the best possible geoscience-based business decisions. They are the framework that permits quantitative integration of multi-disciplinary data across a range of scales in mineral exploration and other critical business applications of geoscience. Successful construction of meaningful structural models that are fully consistent with all observational data and interpretation requires deployment of a “software eco-system” that flexibly connects data structures and 3D visualization to computational capability in geometric interpolation, implicit modelling of faults and horizons, parametric surface construction in sparse data regions, geophysical forward modelling and constrained inversion, and physical property modelling. We have described such a system, which combines GOCAD with several integrated third-party applications. Deployment of such a software ecosystem has been proven, in industry practice, to greatly ease model building effort, create better structural models, and provide a solid framework for making better, faster business decisions than could be done with an older generation of software.

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