Paper 69

Improved 3D Geology Modelling using an Implicit Function Interpolator and Forward Modelling of Potential Field Data

McInerney, P. [1], Goldberg, A. [2], Calcagno, P. [3], Courrioux, G. [3], Guillen, R. [3], Seikel, R. [1]

---

1. Intrepid Geophysics, Brighton, Australia
2. InterOil Corporation, Portsmith, Australia
3. BRGM, France

ABSTRACT

3D geometric modelling is a powerful tool enabling improved understanding of geology. It allows one to check and validate the consistency of separate 1D or 2D interpretations. Building a 3D model is also a way to share and communicate a geological view. Furthermore, a consistent 3D geometric model is essential for modelling computations of Earth-processes (such as groundwater studies) that need an accurate and coherent geometry of the distribution of physical properties of geological bodies. An original methodology has been developed in the BRGM to jointly interpolate geological contact locations and dips of the formations. The method uses the geological history of the area and the rock-relationships between the geological bodies. The model is calculated using an implicit 3D potential function as the interpolator for each component part of that geological history, and allows automatic computation of intersections between component parts and volume reconstruction. By using these tools, the geologist focuses on geological issues and easily tests different interpretations. This methodology has been applied to various geological contexts.

The Elk gas field case-study is presented to illustrate the development of a 3D geology model, and the application of the model for computing conventional potential field model responses. For the Elk field the G_{dd} component of the gravity gradient tensor was computed for the 3D geology model, and those data compared to the first vertical derivative of the fully terrain-corrected Bouguer gravity airborne survey data. These comparisons of the computed vs. observed gravity data provided a basis for several iterations of interpretive adjustment of the 3D geology model. This iterative interpretive revision of the model was only practical by virtue of the ability to rapidly re-compute the 3D geology model using the potential field interpolator methodology. The outcome from this approach was an improved 3D geology model which honoured the available geology constraints from outcrop, drilling and seismic data, but which now had a modelled gravity response that was in better agreement with the observed gravity data.

INTRODUCTION

In recent years there has been growing interest in constructing complete three-dimensional models of geology. Two common challenges are:

- to build a 3D model—often with quite sparse data due to sparse sampling of the geology as a consequence of cover, or the expense of acquiring data at depth.
- to then revise the 3D model as new data are progressively added, or our interpretive understanding of the geology evolves.

It is this latter point—the need to revise the model— which has driven much of the development presented here. Depending on how a model has been constructed, it can be an onerous task to make changes. The solution that is proposed here is to automate the task, and compute a model directly from data (the geologic observations). A revision, then, implies (1) adding the new data, and (2) re-computing the model from the updated database. This new approach has been implemented in a new 3D geology modelling software package—3D GeoModeller.

In this paper, the 3D methodology is discussed in the context of a modelling project completed at the Elk gas field, located in PPL 238 in the Eastern Papuan Basin, Papua New Guinea. The validity of the model was then tested by computing the expected gravity signature of the model and comparing that with the observed gravity data. On the basis of such comparisons several iterations of geologic revision were proposed, a revised 3D model rapidly re-computed and the model gravity response recomputed. The final outcome from this forward modelling work was an improved 3D geologic model which honoured the original geologic constraints, and also had a modelled gravity response that was in good agreement with the observed field data.

In "Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration" edited by B. Milkereit, 2007, p. 919-922

3D GEOMETRIC MODELLING: A TOOL FOR GEOLOGY

The usefulness of 3D geometric modelling to better understand geology is well established (Houlding, 1994, Wijns et al., 2003, Wu et al., 2005). Modelling requires the ability to infer a representation of the reality even where no data are available. This representation can be the final goal of modelling or the geological model can be used to compute simulations to quantify physical processes. In both cases, knowing the geological formation at any place of 3D space is fundamental.

Available tools for 3D modelling are mainly designed for data-rich environments, such as in the petroleum industry with 3D seismic data. Many geology projects, however, are limited to only sparse data or poorly distributed data, with some over-sampled locations such as the surface outcrop or bore-holes, and often little or nothing known between those locations. Furthermore, the interpolation methods used model separate horizons but not intrinsic 3D volumes. Where geology is cyclical, 2D methods are sufficient to construct horizons honouring cross-sections (Galera et al., 2003) but such an approach is restrictive.

Original methods have been developed in the BRGM to answer the question "How to infer the 3D geometry of geological bodies known by sparse and irregularly located data?" These tools are dedicated to geologists wanting to use the geometric knowledge coming from the geological map, cross-sections and bore-holes to test their geological interpretations by building a 3D model. In that scope, the following work has already been successfully applied to orogenic, basin and mining domains (Courrioux et al., 2001, Genter et al., 2004, Martelet et al., 2004, Maxelon et al., 2005, McInerney et al., 2005).

Taking into account both contact locations and orientation data, coherent 3D models are constructed using an implicit scalar method (Lajaunie et al., 1997) to interpolate the data for a formation. The order of geological formations, and their rock-relationships are recorded in the stratigraphic column, which automatically drives the relationships between multiple interpolators used to model multiple formations, making the model easy to refine and to update.

Interpolation method using implicit 3D potential field

The major feature of this original interpolation method is that the 3D geological space is described through a potential field formulation in which geological boundaries are iso-potential surfaces and their dips are represented by the gradients of the potential (Figure 1). A unique solution for the 3D geometry of the interfaces between formations is obtained by assuming that:

- contact data for each interface lie on a potential field surface (an iso-potential),
- orientation vectors are orthogonal to a local tangential plane to the potential field.

On this basis, the field increment (i.e. the change in potential) between any two points belonging to the same geologic interface is null. Orientation data represent the gradient or derivative of the field. The scalar field is then interpolated by cokriging the (null) increment data and their derivatives (Lajaunie et al., 1997). Interfaces (e.g., geologic contacts) are drawn as iso-values of the interpolated scalar field; iso-lines in 2D (Figure 1) or iso-surfaces in 3D.

When the potential field is calculated, the potential value is known for every point at 3D space, with the result that the method is effective for predicting the structure of geology across the broad gaps that exist between sparse data. Furthermore the method can model the sub-parallel geological interfaces of simple, layered geology. A generalisation of this method is required to model more complex geometry.

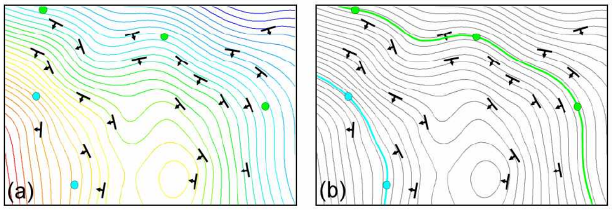

Figure 1: Principle of the geostatistical interpolation using the potential field method. In (a) the contours show the potential field (interpolator) derived from the geology contacts (spots) and geology orientation (strike and dip) data. In (b) two isopotentials of the field are plotted to represent the modelled geology contacts.

Generalisation of the interpolation method with multiple potentials

For the case where the geological history is more complex, and geologic horizons are not sub-parallel, separate potential interpolators must be used - one for each series of strata. For this case it is necessary to define the stratigraphic column, which records the chronological order of the strata, and also the series relationships (either 'onlap' or 'erode'). Where two geologic surfaces from different potential interpolators intersect, an 'erode' surface cuts across any stratigraphically older horizons, whereas an 'onlap' surface would 'stop' against the older surface (Figure 2). This coded information in the stratigraphic column is sufficient to ensure that a unique geological model is constructed from several overlapping potentials. Note that, from a topological viewpoint, the cross-cutting relationships of an eroded contact are no different from the cross-cutting nature of an intrusive contact; thus the 'erode' case is also used to model an intrusive.

This methodology has been applied to various geological contexts ranging from crustal scale modelling, orogenic studies and basin modelling through to urban-scale engineering geology. The basic inputs to the method include field geology observations and data derived from maps, cross-sections, boreholes, etc. The software allows the geologist to test and refine their interpretations and finally to construct their 3D models. Import/export facilities allow the import of field geology and drillhole data, and the export of 3D model shapes for post-processes.

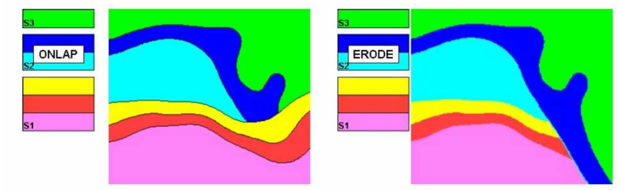

Figure 2: A 2D view of a geologic map or section consisting of three different series of geologic formations. Three interpolators (one for each series) can produce a unique geologic model only with reference to the model's stratigraphic column, which records the chronological order of formations and series, and the relationships between the series. On the left, series S2 'onlaps', and stops against the older S1 series. For the 'erode' case (right) the series S2 cuts across older formations.

ELK EXAMPLE

The Elk gas field is located in PPL 238 in the Eastern Papuan Basin, Papua New Guinea. The field is a structural culmination initially identified by airborne gravity and confirmed by a 2D seismic survey. The Elk-1 well - a discovery well, with a very encouraging gas flow - was drilled to test the oil and gas potential of the fractured Miocene Puri Limestone and the Oligocene to Eocene Mendi Limestone. (Elk-1 location: 145° 08' 27.6" E; 007° 06' 0.5" S).

A realistic 3D geology model (50km x 45km x 10km) of the Elk field was developed using geology information derived from outcrop mapping, field measurements of dip and strike, geology data from two wells and from the geological interpretation of five 2D seismic lines. The model was primarily a study of the targeted reservoir rocks - the fractured Miocene Puri Limestone and the Oligocene to Eocene Mendi Limestone. The overlying Orubadi Formation and Era Beds were included in the model. All of the geology units below the limestone were grouped together into a composite 'Cretaceous' geology unit (Figure 3).

The limestones are anomalously dense relative to the overlying Orubadi Formation and Era Beds (density contrast +0.4 t/m3). The local gravity anomalies observed in the area of the Puri anticline and Elk gas field are due to structural culminations of the dense limestone units. These culminations have developed due to the limestones being ramped up on thrust faults. With overthrusting, there is some repetition of the dense limestone units, which has also contributed to the observed positive gravity anomaly.

Having developed a 3D model of the geology formations, and the interpreted thrust faults - based on the known geology data sources - the gravity response of the model was computed.

The model was discretised to a set of equi-sized voxels (500m x 500m x 200m high), and the geology at the centroid position of each voxel determined from the 3D geology model. On the basis of this voxel geology, density values were assigned to each voxel. The G_{dd} component of the gravity gradient tensor was computed, and compared to the grid of the first vertical derivative of the fully terrain-corrected Bouguer gravity from the airborne gravity survey (Figure 4).

On the basis of such comparisons, revisions were made to the 3D geology model. These adjustments to the model were designed to introduce geological features that might improve the fit between the computed and observed gravity signatures. Several iterations of such adjustments to the 3D geology model, and re-computation of the gravity response were completed (Figure 5). With each iteration the computed and observed gravity signatures were compared to assess whether the fit between the two had improved, and to postulate further revision of the geology model.

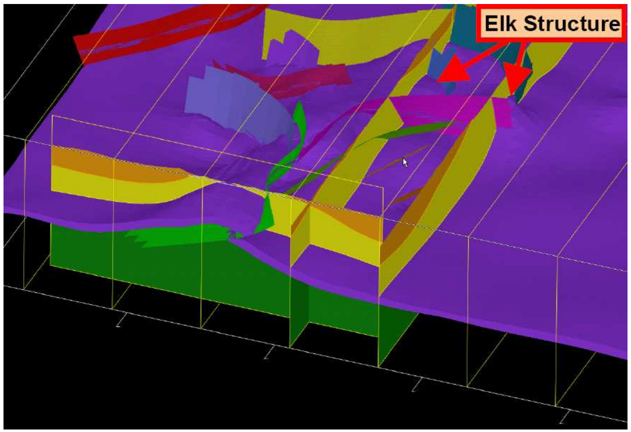

Figure 3: Perspective view of the final 3D geology model, showing the Puri and Mendi Limestone horizon and thrust faults.

Two critical factors which enabled this iterative revision and ultimate improvement of the 3D geology model were (1) the ability to rapidly build a revised 3D geology model using the implicit function interpolator, and (2) the rapid re-computation of the geophysical response of the revised geology model. This interpretive revision of the model would not have been practical if the model-building process had required laborious, manual adjustment of the model. Instead, the use of an automated rapid model construction allowed the interpreter to remained focused on the practical, geological interpretive considerations of the work.

The result was an improved 3D geology model which honoured the available geology constraints from outcrop, drilling and seismic data, but which now had a modelled gravity response (Figure 4b) that was in better agreement with the observed gravity data (Figure 4a). The study produced an improved understanding of the structure of the Elk field, an area with limited seismic control. It is postulated that NE-SW oriented faults (introduced to the geology model) have vertically offset the elevation of the target Puri/Mendi Limestones.

ACKNOWLEDGMENTS

Software package for 3D GeoModeller can be found at http://www.geomodeller.com.

REFERENCES

Courrioux, G., Nullans, S., Guillen, A., Boissonnat, JD., Repusseau, P., Renaud, X., Thibaut, M., 2001. 3D volumetric modelling of

Cadomian terranes (Northern Brittany, France): an automatic method using Voronoï diagrams. Tectonophysics (331) : 181-196.

Galera, C., Bennis, C., Moretti, I., Mallet, J.L., 2003. Construction of coherent 3D geological blocks. Computers & Geosciences (29) : 971-984.

Genter, A., Giot, D., Bertin, C., Bitri, A., Calcagno, P., Courrioux, G., Dagallier, A., Giraud-Petelet, E., Goyeneche, O., Martelet, G., Millot, R., Négrel, P., Rocher, P., Serra, H., Serrano, O., Vairon, J., 2004. Méthodologie d'inventaire du potentiel géothermique basse et moyenne énergies en Limagne. Rapport final. (BRGM/RP-53463-FR) : 105 pp.

Houlding, S.W., 1994. 3D geoscience modelling. Computer techniques for geological characterisation. Springer-Verlag (ISBN 3-540-58015-8) : 309 pp.

Lajaunie, C., Courrioux, G., Manuel, L., 1997. Foliation fields and 3d cartography in geology: principles of a method based on potential interpolation. Mathematical Geology (29) : 571-584.

Martelet, G., Calcagno, P., Gumiaux, C., Truffert C., Bitri, A., Gapai, D., Brun, J.P., 2004. Integrated 3D geophysical and geological modelling of the Hercynian Suture Zone in the Champtoceaux area (south Brittany, France). Tectonophysics (382) : 117-128.

Maxelon, M., Mancktelow, N.S., 2005. Three-dimensional geometry and tectonostratigraphy of the Pennine zone, Central Alps, Switzerland and Northern Italy. Earth-Science Reviews (71) : 171–227.

McInerney, P., Guillen, A., Courrioux, G., Calcagno, P., Lees, T., 2005. Building 3D geological models directly from data? A new approach applied to Broken Hill, Australia. Digital Mapping Techniques 2005 Workshop in Baton Rouge.

Wijns, C., Boschetti, F., Moresi, L., 2003. Inverse modelling in geology by interactive evolutionary computation. Journal of Structural Geology (25) : 1615–1621.

Wu, Q., Xu, H., Zou, X., 2005. An effective method for 3D geological modelling with multi-source data integration. Computers & Geosciences (31) : 35–43.

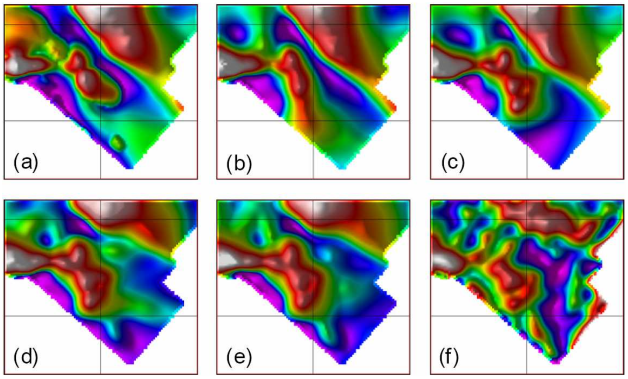

Figure 5: Comparison of computed gravity responses. Images (a) to (e) show the G_{dd} response computed from a subset of the evolving 3D geology models developed during the study. Image (e) is computed from the final model. Image (f) is the 1VD of the observed gravity.

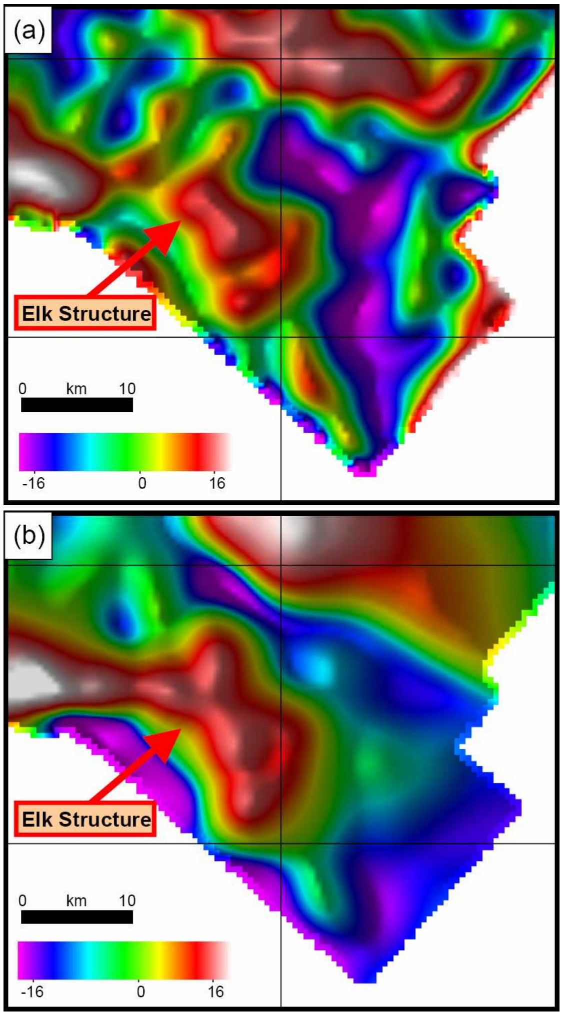

Figure 4: Elk gas field observed vs. modelled gravity signatures, showing the gravity high associated with the Elk structural culmination in the dense limestone. Image (a) is the first vertical derivative (1VD) of the fully terrain-corrected Bouguer gravity anomaly data from an airborne gravity survey dataset. The modelled gravity response (b) is the G_{dd} component of the gravity gradient tensor (equivalent to 1VD). The two images are displayed using the same colour stretch.