Creation and Delivery of Multi-scalar GOCAD™ Models for the UK 3D National Geological Model: Examples and Issues from Scotland.

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Abstract

The depth dimension of conventional geological maps is very difficult for non-geologists to appreciate. As a result, decision makers rarely take full account of subsurface geoscience issues in planning and development; nor do they fully exploit potential subsurface assets. With the advances of 3D software and ever increasing hardware processing power, it is now possible to combine large quantities of disparate geoscience data types for a wide range of applications, to display these data effectively and in ways that non-geologists can easily understand, to inform their decisions.

Using several 3D modeling packages, but primarily GOCAD® workflows, we have created 3D models designed to 'nest' within each other. Lower resolution regional and catchment models (1:50,000 to 1:250,000-scale equivalent) provide the context for higher resolution (1:10,000-scale equivalent), and site-specific, models, mainly of urban areas and infrastructure corridors. The geological framework models have been attributed with a wide range of parameters such as permeability, aquifer productivity and various engineering properties. They have also been exported to flow modelling packages to model time-series processes such as recharge and flow of groundwater, and will be used to model migration of contaminant plumes and carbon dioxide. Man-made objects, such as tunnels and mine workings have been embedded as 3D objects and placed into the 3D geological framework so their relationships to faults and other geological structures can be examined.

These multi-scalar models form an important component of the BGS's National Geolological Model. However, the greatest remaining challenge is both delivering such models in a format that a wide range of non-specialist users can understand, their use in risk management and conveying the varying certainty on any modeled surface.

Introduction

Glasgow is Scotland's biggest city with a population of approximately 1.2 million. As with many other industrial cities built on coal and ironstone deposits, there was extensive mining in Glasgow during the 19th and earlier parts of the 20th centuries. This has resulted in large parts of the city being undermined, often at shallow levels (Campbell *et al.* 2010). This post–industrial landscape has been targeted by the Scottish Government as a national regeneration priority. This has meant that a large number of users, from Government and local authorities to private developers, need to be able to see and understand the often complicated geological relationships under Glasgow. This is important for purposes as diverse as contaminant remediation to ground subsidence, and ground source heat from mine waters.

The British Geological Survey (BGS) has, over the last 15 years, been extensively engaged in the creation and development of geological 'framework' models as part of the National Geological Model (Jackson and Green 2003; Smith *et al.* 2005; Merritt *et al.* 2007; Ford *et al.* 2008; Burke *et al.* 2009; Kessler *et al.* 2009; Royse *et al.* 2009; Ford *et al.* 2010; Campbell *et al.* 2010). These have used a variety of 3D modeling packages; however in coalfield areas such as around Glasgow, GOCAD® has been invaluable in dealing with the range and distribution of data available.

The modeling workflows and methods adopted in Glasgow therefore provide an excellent example of the challenges that need to be addressed in the development of GOCAD® modeling in urban environments across the UK and further afield. Also, this work highlights the issues that can occur when delivering such models to a diverse user community of differing abilities and interests.

1. Users of the data and need for geological understanding

One of the aims of the Clyde-Urban Super-Project (CUSP) is delivery of 3D models for Glasgow City Council and other local and regulatory authorities (Figure 1). This includes collaborating with partners from widely differing backgrounds, such as trans-disciplinary linkages with socio-economists, environmentalists and health experts, many of which have little or no geological background (Campbell *et al.* 2010). Understanding how geological units relate in three dimensions is hard for these non-specialists to appreciate from a conventional geological map. 3D geological models provide a useful platform to disseminate complicated geological relationships.

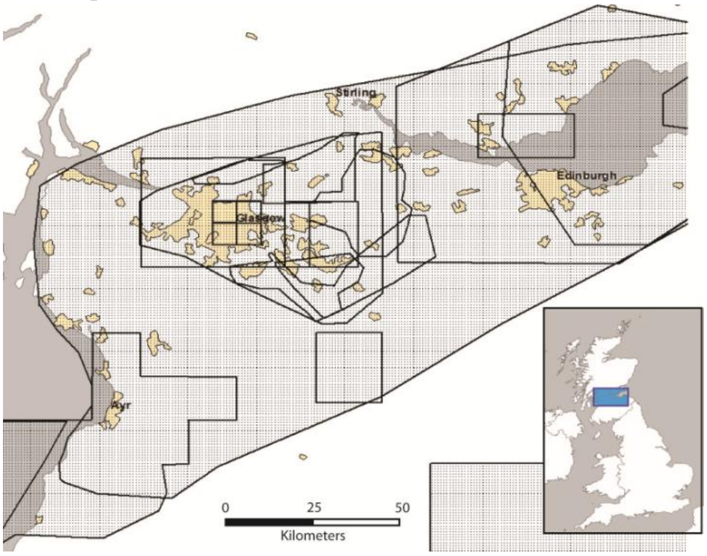

Figure 1 Map showing the areas of GOCAD models created in Scottish coal field (stippled area)

Different users are interested in using models at different scales (Figure 1). For instance, Government or a City Authority may be interested in the regional extent of a certain unit to quantifying or regulate a resource, such as ground source heat. However, private developers and those involved in site remediation, are interested at a site level. It is hard to create models to satisfy both these groups of users, and the uneven distribution of data available to model with means the models are of variable accuracy across the area. To address this we have created regional and catchment models (c. 1:250,000 to 1:50,000-scale equivalent) to satisfy the demands of those interested in regional variation.

For site specific models we encourage contractors to get in contact with BGS directly so we can create 'bespoke' models at a scale to suit them. With these models the contractor is encouraged to provide their own site investigation information so it supplements BGS's regional datasets.

2. Model input data

Four sources of input data were available to constrain the GOCAD® modeling: geological maps, boreholes; mine abandonment plans and seismic data.

2.1. Geological Maps

The most geographically extensive sources of geological information for the study area are the BGS geological maps. There are twelve 1:50 000 scale geological map sheets that cover the Clyde catchment area (http://www.bgs.ac.uk/products/digitalmaps/digmapgb_50.html). The outcrop lines from the maps were used to define where stratigraphical horizons, coal seams and limestone beds come to surface. Where possible, the highest resolution 1:10 000 scale maps, which were used to create the 1:50 000 geological maps sheets were used. The geological maps are also the primary source of information on fault surface traces and throws.

2.2. Boreholes

The BGS holds 95301 digital borehole records for the Glasgow area. These held in the digital corporate Oracle databases 'Single Onshore Borehole Index' and 'Borehole Geology' databases (see Kessler *et al.* 2009 for further information). However, most of these boreholes are shallow (<10m) and there are only 1800 boreholes which record a sufficient thickness of strata to aid 3D bedrock modeling. Most of these boreholes were drilled to investigate coal, limestone and iron resources during the early and mid 20th century, additionally, a small number of boreholes were drilled by the BGS and major oil companies to depths greater than 1000 meters which provide detail of the regional stratigraphy. For the stratigraphic intervals that have not been mined, these represent the only sub-surface control data available.

2.3. Mine Abandonment Plans

Mine abandonment plans are archived by the BGS, in common with the Coal Authority, for most of the major coal seams in Scotland. These represent a wealth of data to constrain 3D models including depth values of a particular coal seam along with the underground position of any faults and the position at which the coal seam comes to outcrop. These were digitized using ArcGIS (Figure 2) and any height or level information converted in to depths with respect to British Ordnance Datum. These were used as the primary control data for many of the modeled surfaces.

Figure 2 An example of digitized mine plan information

3. Model creation

The greatest issue when creating GOCAD® models in coal field environments is the variability in the density of control data for any stratigraphic surface relative to the complexity of the surface. The coal field strata of the Glasgow area have been affected by several periods of faulting and have been gently folded, both locally due to the faulting, and regionally. However, the data that can be used to constrain the surfaces is not evenly distributed on any particular stratigraphic surface (Figure 3).

Equally, the control data is variable for each surface. In the regional and catchment models there were 16 separate stratigraphic surfaces modeled in the Glasgow area (Figure 4). Of these, four surfaces extended across the whole area of the model (Base Scottish Lower Coal Measures Formation; Base Index Limestone Formation; Base Limestone Coal Formation; Base Lower Limestone Formation (Hurlet Limestone)). Eleven surfaces are constrained by mine plan, borehole and outcrop data. The other 5 are only constrained by borehole and map outcrop information (Figure 4).

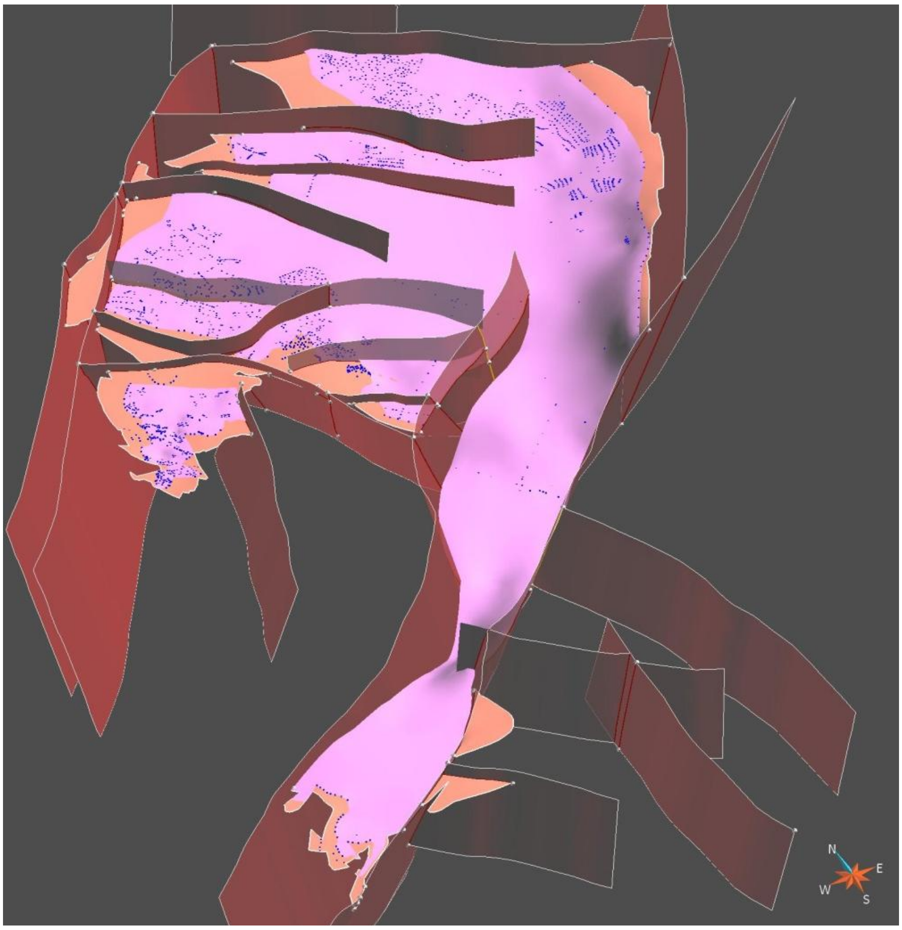

Figure 3 Example of variable data density constraining a coalfield model – blue dots on pink surface represent mine plan, borehole and outcrop data on a coal seam

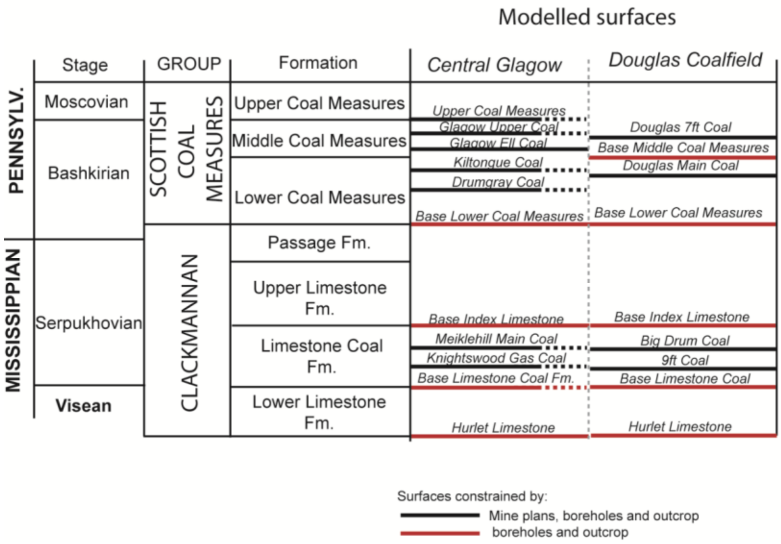

Figure 4 : The stratigraphic surfaces modeled in the regional and catchment models

3.1 Modeling workflow

The 3D geological models were constructed using GOCAD® software based on borehole data points, mining data, map outcrop data and geologist-interpreted data. A standard workflow of importing and collating 2D and 3D data, importing fault pattern information and constructing appropriate fault geometries, and application of the GOCAD® Structural Modeling Workflow was undertaken. This was followed by multiple manual iterations and editing to better constrain the model and remove crossovers. The heterogeneous data density and relatively complex geology necessitates the addition of interpretive data and fault-horizon editing. A variety of different methods have been used to capture interpretive data and geological knowledge:

1. Geologist addition of interpretive points using GOCAD® cross-sections after initial calculation has identified problem areas (generally used for horizons with mine plan data)
2. For horizons with very sparse data control, geologist addition of interpreted data from outcrop data or higher surface observed data projected downwards with a constant average thickness derived from published stratigraphic columns or borehole interval thicknesses.
3. Geological fault modeling and horizon interpretation in GSI3D and model calculation in GOCAD®. GSI3D methodology for model construction is described by Kessler et al. (2008); it principally involves the construction of cross-sections between surface and subsurface datasets.

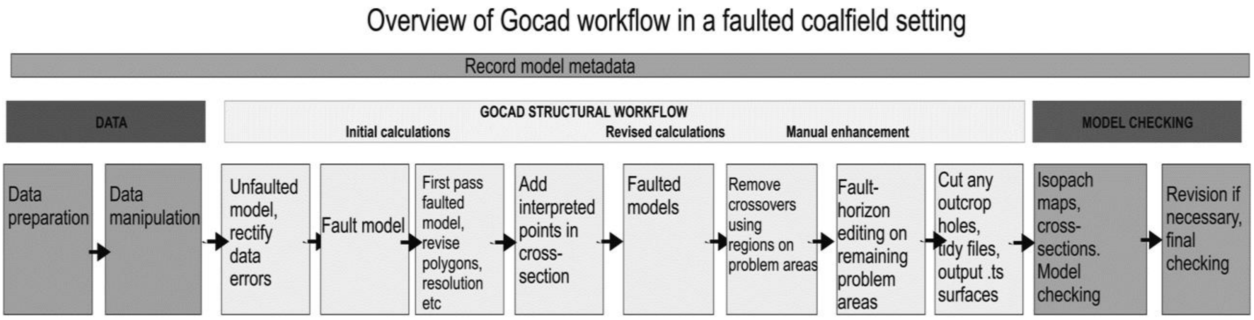

Figure 5 Overview of GOCAD® methodology in a faulted coalfield setting

3.2 Fault modeling

Different methods have been used in the construction of faults. The majority of models had little subsurface fault information and in this case faults were projected down from surface at a constant dip value across the model and had their edges and sides 'squared' off (Figure 6A). In areas where there was plentiful digital mine plan information captured it was possible to use fault information from the mine plans to define changes in fault dip and orientation with depth. This facilitated the creation of more realistic fault networks (Figure 6B).

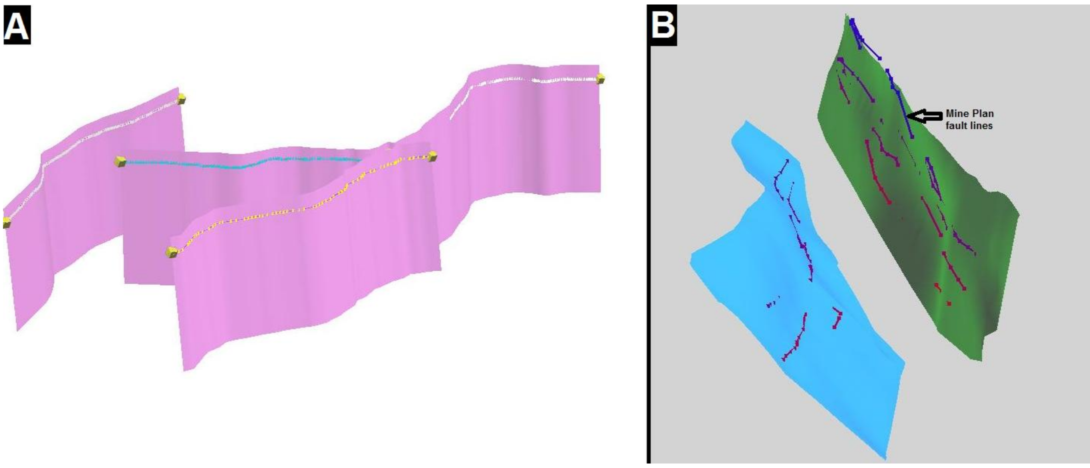

Figure 6 A. the method of creating faults by projecting down from outcrop traces. B. faults modeled using mine plan fault traces.

3.3. Mutliscalar consistency

The main differences between models made at different scales are the densities of triangle on a surface. This is influenced by the resolution and detail of bounding outcrop curves and the size of faults included within a model. Regional scale models contain only the larger faults, whilst site specific models contain all but the smallest mapped fault structures. To enable consistency between models at different scales, high resolution models are resampled for inclusion in lower resolution models, and high resolution models take credence of horizons and faults modeled regionally. Edge matching of adjacent models was undertaken as modeling progressed. These multi-scalar models form a key part of BGS's National Geological Model and have been utilsed by a number of users.

4. Methods of data delivery

The greatest challenge facing the uptake and use of 3D geological models is how they delivered to the end user. It has been noted that planners, engineers and other potential users of geological information in an urban environment are less likely to be able to interpret geological information (Culshaw and Price 2011), and furthermore, it must be delivered in a format that is instantly understandable to the end user (Culshaw 2005).

4.1 2D Delivery

When attempting to deliver GOCAD® models to the range of end users wishing to utilize urban models, there are two distinct problems: 1) Very few urban- users use GOCAD® or compatible software; 2) Many users are not accustomed to 3D models and would rather their deliverables be in a 2D format, but still retain the added value that 3D models deliver.

BGS uses a variety of methods to deliver 3D model information (Lithoframe Viewer http://www.bgs.ac.uk/services/3Dgeology/lithoframeSamples.html , section and borehole viewer http://www.bgs.ac.uk/services/3Dgeology/virtualBoreholeViewer.html) but delivery of complex faulted bedrock information to non-specialists remains difficult. Currently faulted bedrock models are most commonly delivered as 3D PDF's, and/or ASCII or ARCGIS grids, or as a derived, customised output (e.g.mining within 30m of rockhead).

In the Glasgow Urban area one of the greatest problems to any development is hazards relating to former mine workings. These have an impact both on construction and movement of any contaminants through the sub-surface (Browne *et al.* 1986). It is possible to extract from the GOCAD® model surfaces representing the worked areas of those coal seams that we have digitized information for. These can then be interrogated and either contour map created, or raster grids created, which show the closeness of said working to the ground surface (Figure 7) and/or rockhead surface.

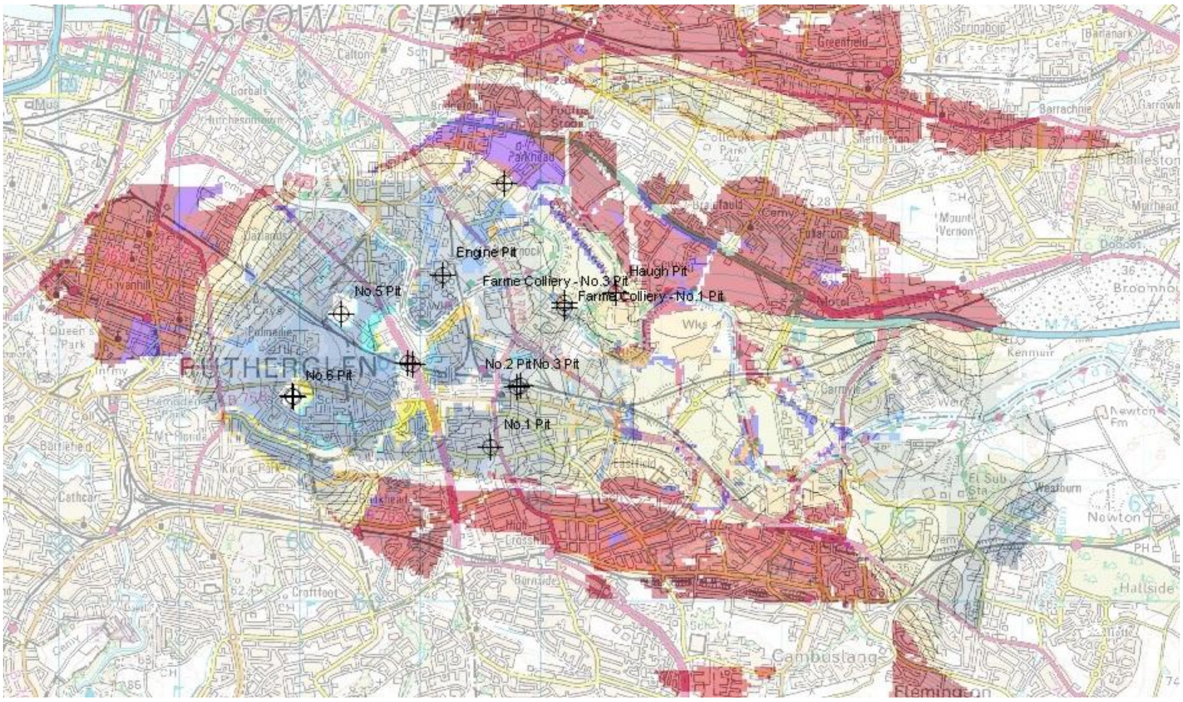

Figure 7 A raster grid from a GOCAD® model showing depth below surface of a particular coal seam

4.2 Embedded infrastructure

Many users wish to see how man-made objects relate to geological features. In the Glasgow area this often involves understanding how old coal mining infrastructure relates to geological fault structures and how it may act as a potential pathway for contaminants. In this case the 3D relationships between these features are needed to be understood by the client. In these situations mine shafts can be created by utilizing the channel making methodology in GOCAD® and the drives and workings by cutting the relevant parts of the surface and using the surface creation tools outside the GOCAD® workflow to produce accurate 3D representations of these objects (Figure 8). These are often delivered to the client in the form of a 3D PDF document. However, this format does not allow the user to actively interrogate the model and a free platform which any user can interrogate a model is required. It would be an advantage if this platform was web based limiting the need for the client to install bespoke software on their system.

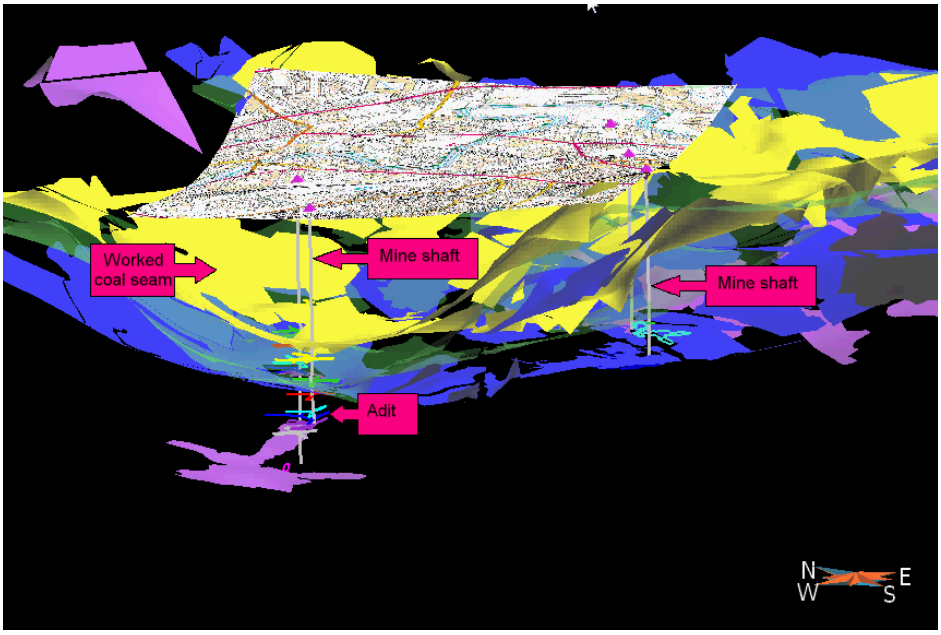

Figure 8 Old coal mining infrastructure superimposed upon modeled surfaces cut to the extent of known mine workings (x 10 vertical exaggeration)

4.2 Uncertainty

When utilizing such poorly distributed datasets as those available in urban areas it is critical to give the user an understanding of how the controlling data varies across the model and how this affects the certainty of the model. The uncertainty of a model is not restricted to the algorithms that make up the model, but involves all the factors that feed into the model development, including subjective data (Lelliott *et al.* 2009). The BGS has developed several methods to represent uncertainty in models (e.g. Riddick *et al.* 2005; Lelliott *et al.* 2009). Key in this development is that any such method should take into account the variable certainty in the input and constraint data of a surface and the complexity (rate of change) of the surface, along with any uncertainty that results from the surface creation algorithm (Figure 9).

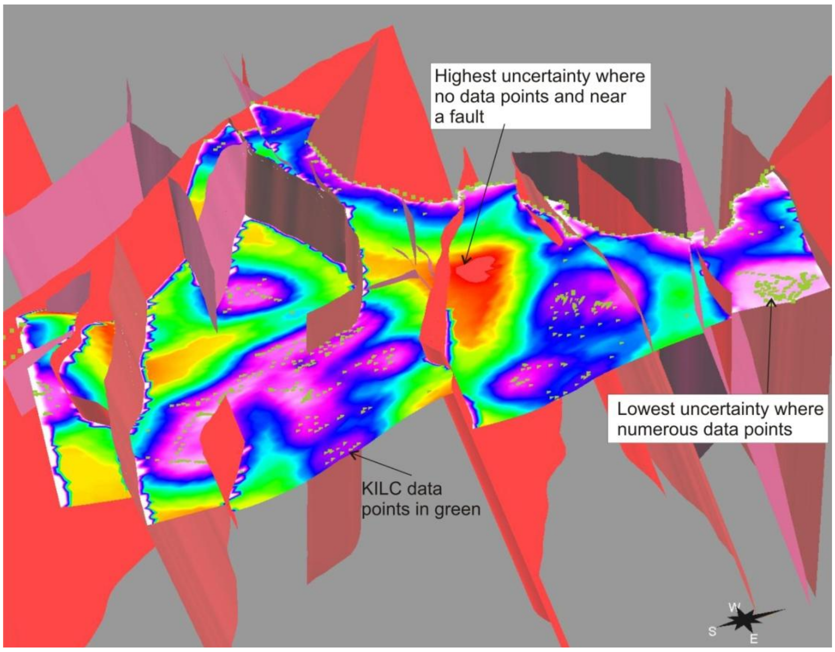

Figure 9 Example of uncertainty property for a coal seam draped on the geological surface in GOCAD®, red areas with highest uncertainty, pink areas with lowest uncertainty.

Conclusion

GOCAD® has proven itself invaluable in dealing with relatively complex faulted and folded geology together with the heterogeneous distribution of data available in urban coalfield environments. Using a range of different workflows it is possible to create 3D geological models of coalfield areas which can form the basis for simulations or to aid non-geologists to understand complicated geological sequences.

The greatest remaining challenge for such models is both delivering such models in a format that a wide range of non-specialist users can understand and conveying the varying uncertainty in any surface created in the model.

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