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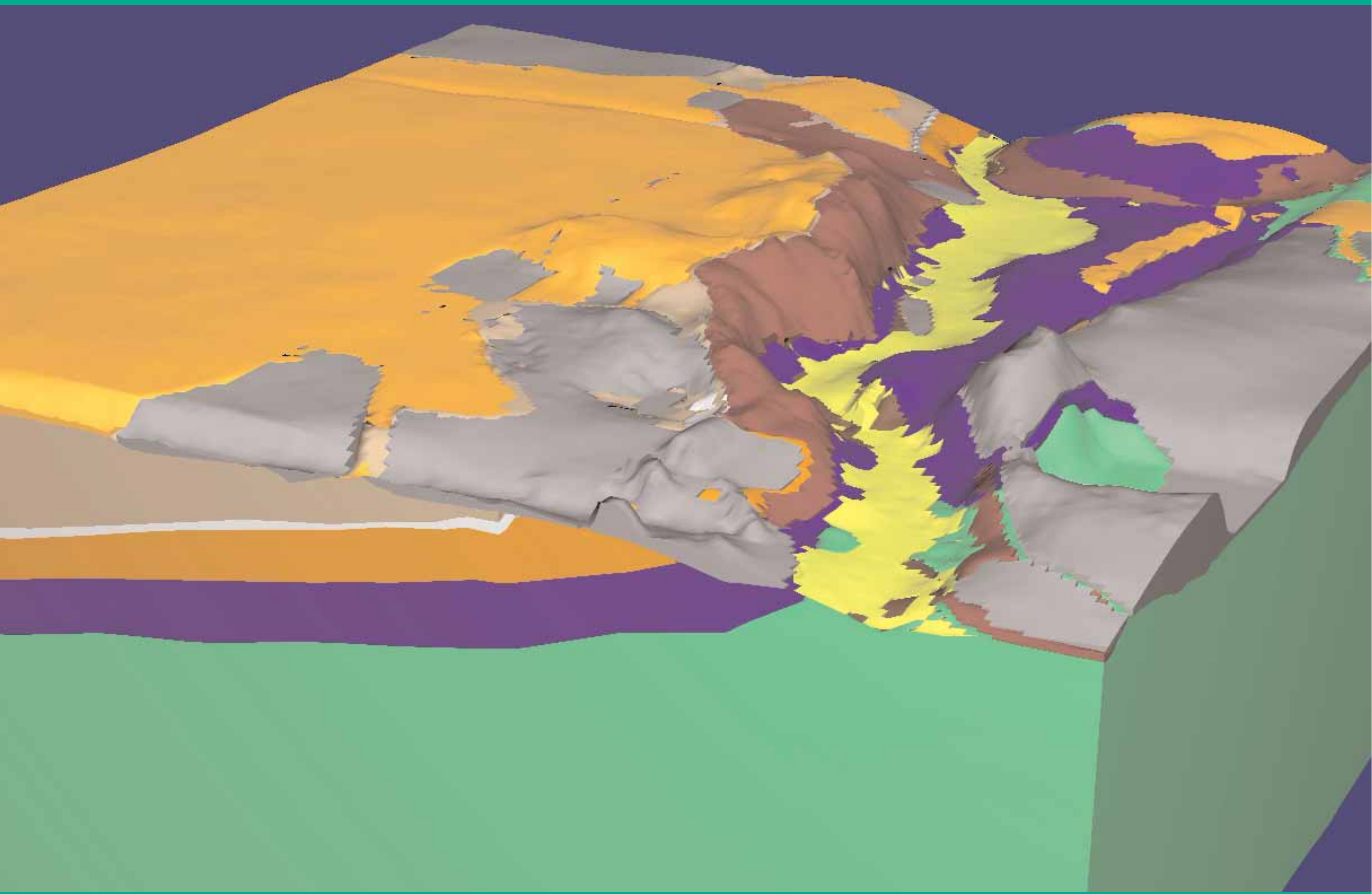

DIGITAL GEOSCIENCE SPATIAL MODEL PROJECT FINAL REPORT

DGSM Programme. British Geological Survey Occasional Publication No. 9

BRITISH GEOLOGICAL SURVEY

OCCASIONAL PUBLICATION NO. 9

DIGITAL GEOSCIENCE SPATIAL MODEL PROJECT FINAL REPORT

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Maps and diagrams in this book use topography based on Ordnance Survey mapping.

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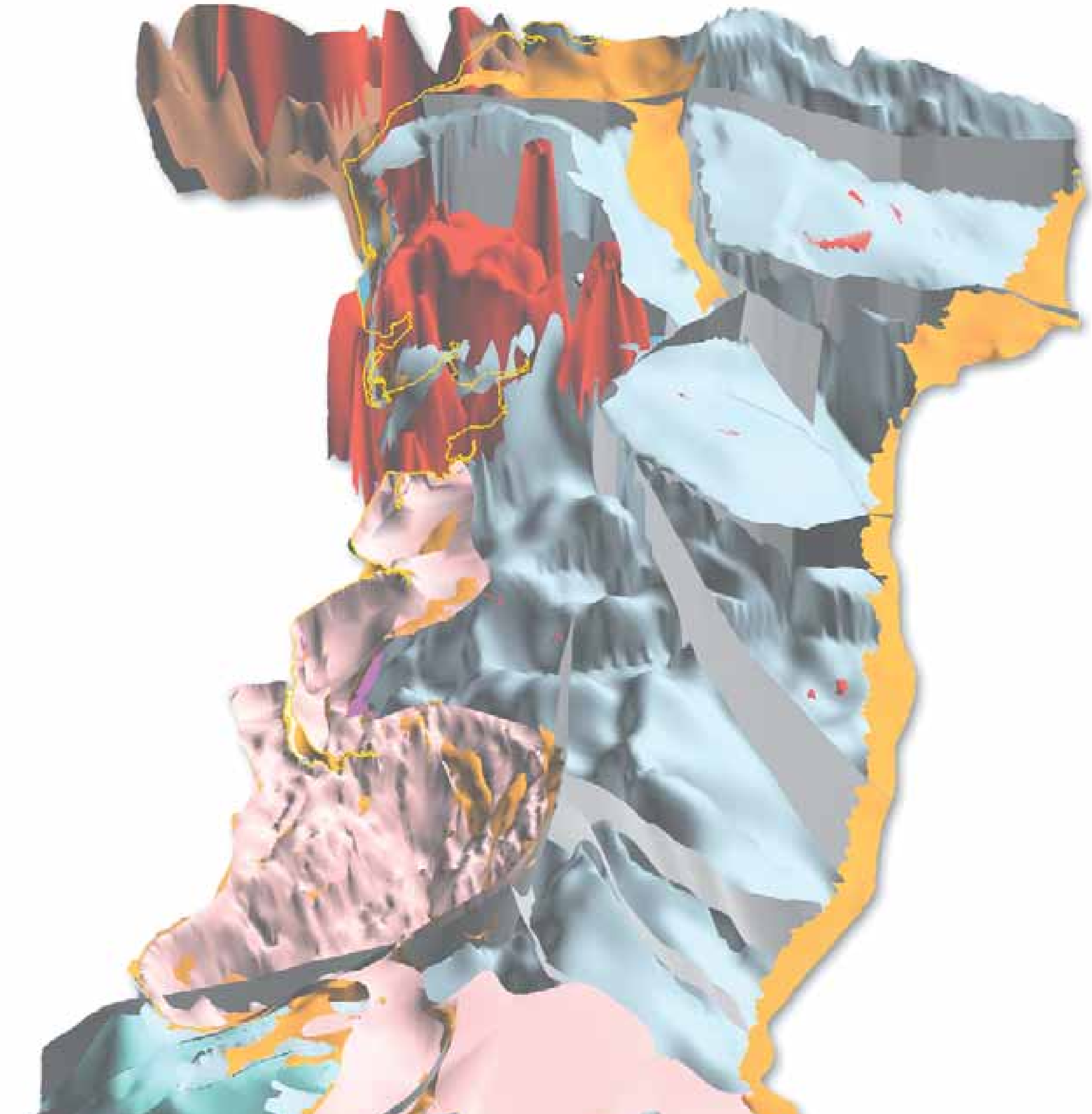
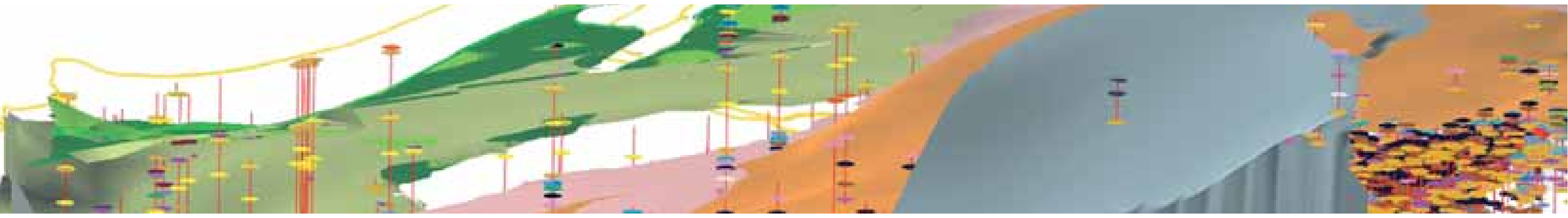
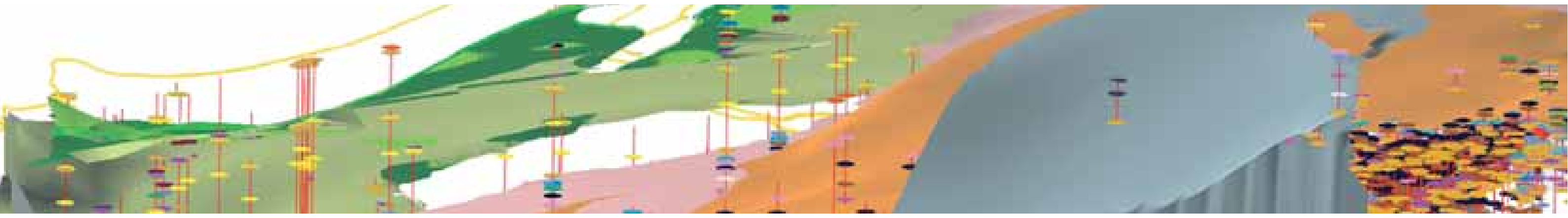




Contents



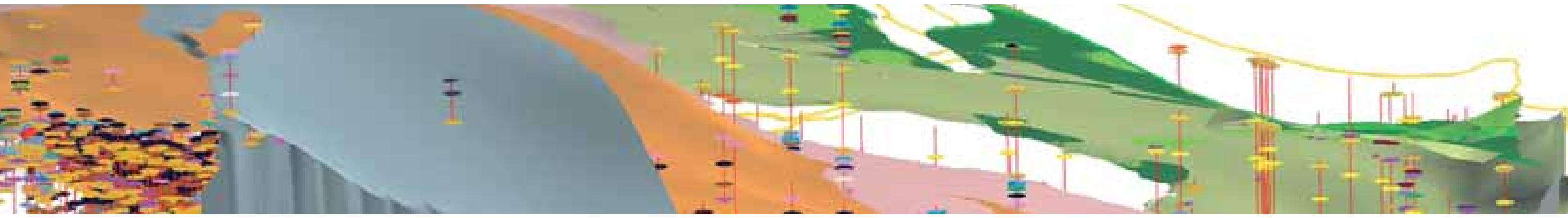
Foreword

Geology is inherently a 3D science. Geologists have a 3D model in mind as they develop an understanding of an area. When we build a digital model we are using information technology to convert this mental image into a tangible product. This allows us to share our understanding of the concealed geology.

It is our responsibility, as a national geological survey, to provide baseline geoscientific information for the nation. Traditionally, and because of the limitations of paper the map has been used to show surface geology with concealed surfaces represented by sections or structure contours. The Digital Geoscience Spatial Model project has created an operational production environment in which consistent and systematic digital models can be prepared, manipulated and visualised. These models fully exploit and make accessible the great wealth of subsurface information the BGS holds. The models can then be provided in digital form for visualisation and use in computer applications.

The success of this project has depended on the diverse and broad experience of BGS geoscientists plus the expertise of a large group of information systems specialists. Together they have created a working environment that will provide solutions to many of the geological problems faced by our clients.

D A Falvey
Executive Director, BGS



Acknowledgements

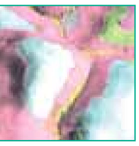
This report is an opportunity to recognise the contributions made to the DGSM project by so many people across the British Geological Survey. The quality of their work has been exemplary, as has their insight into problem solving and continually evolving technology.

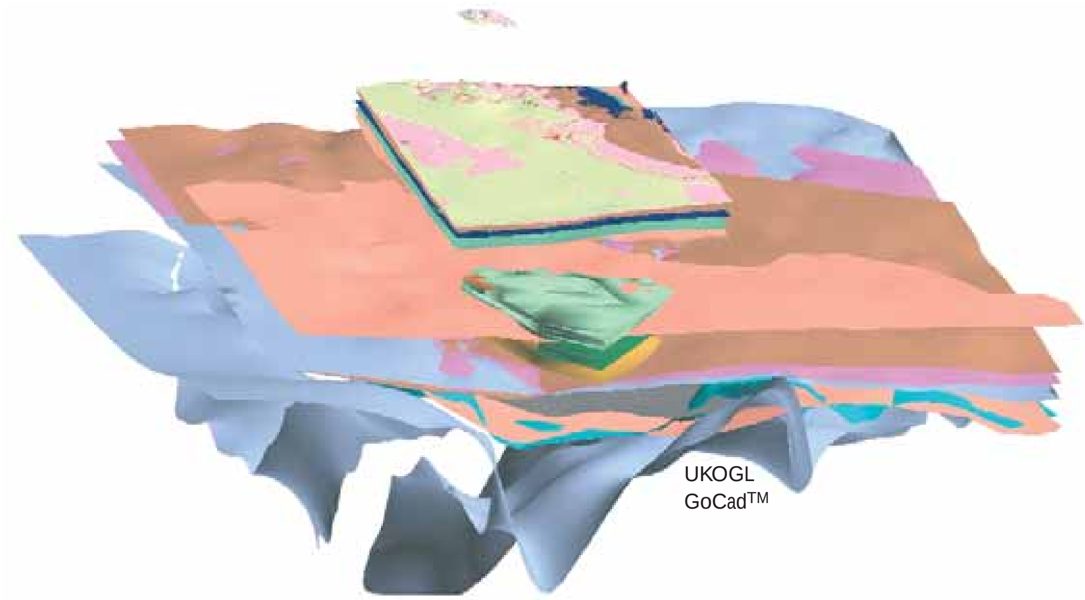
I would particularly like to thank Stella Carter, a long-suffering personal assistant for the project and Richard Shaw, the DGSM operations manager who has been a stalwart in keeping the project milestones on track. The project has been overseen by the DGSM Steering Group consisting of Bill Hatton, David Holmes, Ian Jackson, Mick Lee and Roger Scrutton. They have provided a strong sense of focus and direction. I am grateful for their wisdom and good humour.

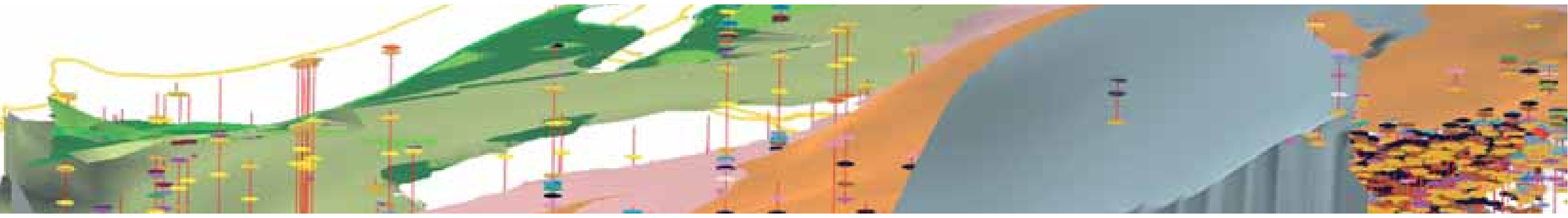
The Natural Environment Research Council (NERC) provided funding to enable the team to put real commitment into the project in the knowledge that adequate resources were available. I am grateful that they responded to our initial proposal in such a constructive way.

Finally, my personal thanks to the British Geological Survey, an organisation which has provided me with a wonderful range of opportunities over my career. I hope that the DGSM will stimulate many more exciting opportunities for new development and interesting projects in the years to come.

Ian Smith
DGSM Programme Manager







Introduction

When developing a 3D view of the subsurface, a geologist has to collect, validate and integrate a wide range of data. The resulting understanding of the concealed geology can then be brought together as a 3D model. All of this data and understanding should be accessible as the model is viewed, rather like a digital 3D geological map with descriptions, keys and links to the observational data. The term digital geoscience spatial model (DGSM) was coined by Vic Loudon for this concept, which he describes in the first section of this report. The DGSM has seen the concept turned into a working system.

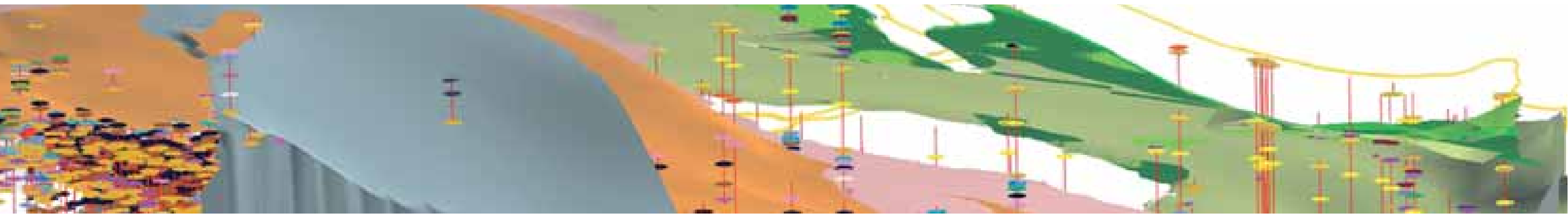
In this report we summarise the objectives and achievements of the DGSM and describe the strands that have been woven together to bring the programme to completion. Our intention here is to provide an outline of the system so that BGS colleagues, other environmental scientists and our clients can use it to further their understanding of the complex Earth on which we depend. In order to put the idea into practice, the BGS carried out a scoping study and won funding from the NERC to carry out a five-year project which started in 2000.We designed the programme to have two main parts: the 'framework' of information technology developments and the 'population projects' where the framework could be tested.

The central principle in the design of the DGSM has been extensibility.This means ensuring that developments are built on the sound standards set by the earlier BGS-geoIDS project that can be re-used and integrated with future developments. It would be a poor investment if the outcomes of the DGSM programme, however elegant and powerful, did not contribute towards a long-lasting and robust infrastructure for BGS projects. While the system has been designed for geoscience, it could be adapted to any spatially referenced earth or environmental science. The methods should enable collaboration between a wide range of disciplines.

Putting the idea into practice

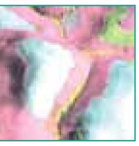
We have created and linked together a framework of databases, applications, standards and procedures. This means that the digital products of multidimensional modelling can be described, archived and accessed. We have tested the framework with newly created models from a range of differing geological terranes. The geoscience community will therefore be able to use the system with confidence when applying it to their own needs. These might involve building new systematic models to corporate standards, populating databases or providing enquirers with information on request.

The purpose of this report is to show how we have used the significant levels of funding from the NERC to make progress in the way we carry out our science. If DGSM technologies really change the way that geoscience is appreciated, then the programme as whole will have succeeded.



Background

The work of geological surveys worldwide has long focussed on the geological map, following well-established procedures and formats. Geologists took these for granted and concentrated on understanding the geology. Although the map's future is not in doubt, more flexible products are emerging. Successive waves of developing technology are disrupting the ways we present geology, eroding weak areas and bringing in new concepts, only to be disrupted in turn by the next wave.



For example, digital cartography helps with the laborious and time-consuming tasks of map drafting and editing. But automation in the drawing office still creates maps constrained by their static two dimensions, fixed scales, inflexible information density, limited topics, and rigid sheet boundaries. Maps inconveniently separate the spatial depiction from the geological interpretation contained in text descriptions and explanations, field records, and data.

The major benefits of information technology generally come, not from automating existing procedures, but from enabling the underlying requirements to be tackled in new ways. Geological surveys with this in mind reconsider their basic objectives, no longer defining them in terms of established products.

Thus, the DGSM and associated projects build on digital cartography, but take a broader view. The computer can readily handle 3D spatial models. The information can be organised as surveyed instances of objects (categories such as observations, outcrops, rock bodies, stratigraphic units, folds and faults) at appropriate levels of detail, rather than as map sheets of fixed scale. In turn, object instances can be assigned to more abstract object classes, matching patterns of human thought. Hierarchies of object classes correspond to existing classifications, such as those for stratigraphical units, fossils, rock or mineral types.

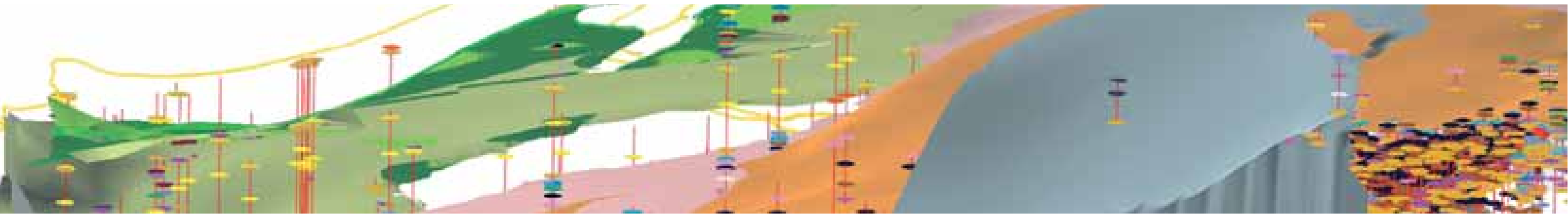
Spatial and explanatory information can be integrated at any level of detail by connecting items, for example through web links. This applies within and between various information environments, probably displayed as separate windows on the computer screen.

- In the metadata (data about data) environment we can determine what information is available, how it is defined, what form it takes, and how to find it, regardless of mode of representation.
- In the spatial environment, we can look at the context or select the area of interest by panning, select content by filtering, add detail or generalise by zooming in or out, find effective visualisations by experiment, detect patterns by inspection, and compare spatial distributions by overlaying.
- In the narrative text environment, we can follow threads of reasoning, and find relevant accounts with search engines, tables of contents, and indexes. We can link to generalisations in abstracts and textbooks, or find context and detail through references to related papers, field records and databases.
- In the database environment, we can select information according to the values of its properties, using query languages. We can look at detailed raw data or generalise by statistical summary or analysis.

Geologists examine data from many external sources and try to reconcile their interpretation with them. In the DGSM, they can identify the sources and record the reasoning and reconciliation processes. The resulting knowledge base can be filtered for relevant material, and examined on screen.

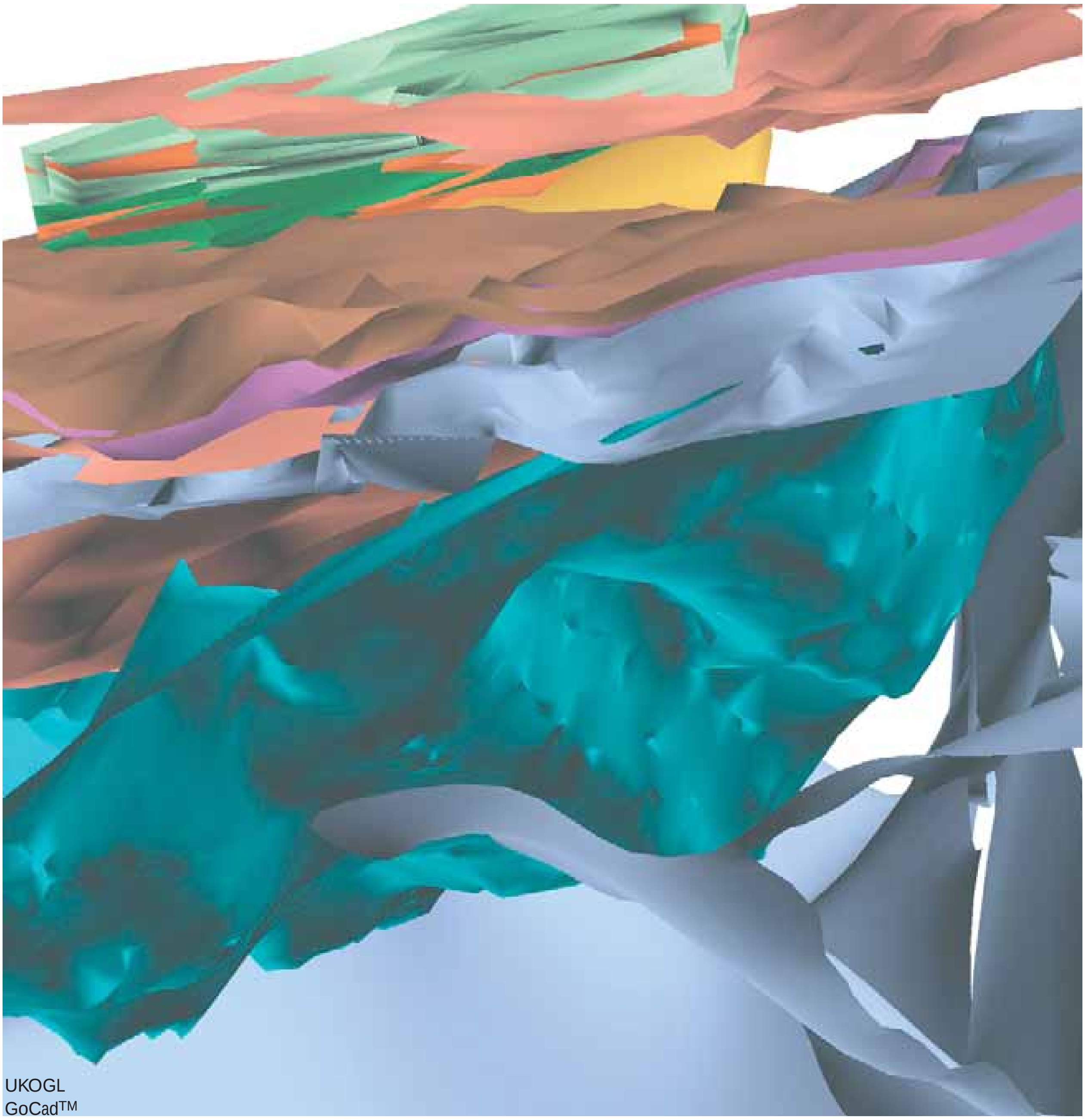
Because external information was collected for diverse purposes (commercial, academic), aspects that do not contribute to the survey map may nevertheless be significant for some users. They might wish to access this broader information through thematic maps or, as they presumably know their own requirements best, by selecting topics, area, scale and mode of visualisation for their own purposes.

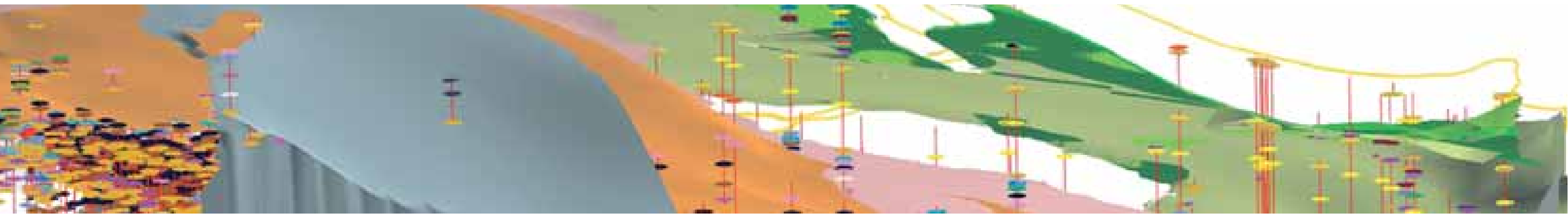
The DGSM enables geologists to offer a more comprehensive interpretation, and users to obtain more relevant and accurate information. It extends the knowledge base, ready for the next wave of technology. The internet is evolving into the grid — a ubiquitous knowledge infrastructure, supporting web services that hide complexity from the users, to be shared by all and taken for granted like the electricity grid. The irreplaceable legacy of geological survey information may evolve in parallel, to occupy a future niche as a set of web services integrated within the mainstream standards of the global knowledge system. The DGSM marks a significant step along the way.



Background

The DGSM Project was divided into two sections: the framework projects and the population projects. The framework projects have developed methodologies, systems and databases to facilitate 3D modelling in the BGS. The population projects have built a range of models, representative of different aspects of UK geology, at a range of resolutions and using different modelling software packages. The primary aim of these models was to test the systems and databases developed by the framework projects. All DGSM projects are summarised in the following pages.





THE DGSM FRAMEWORK

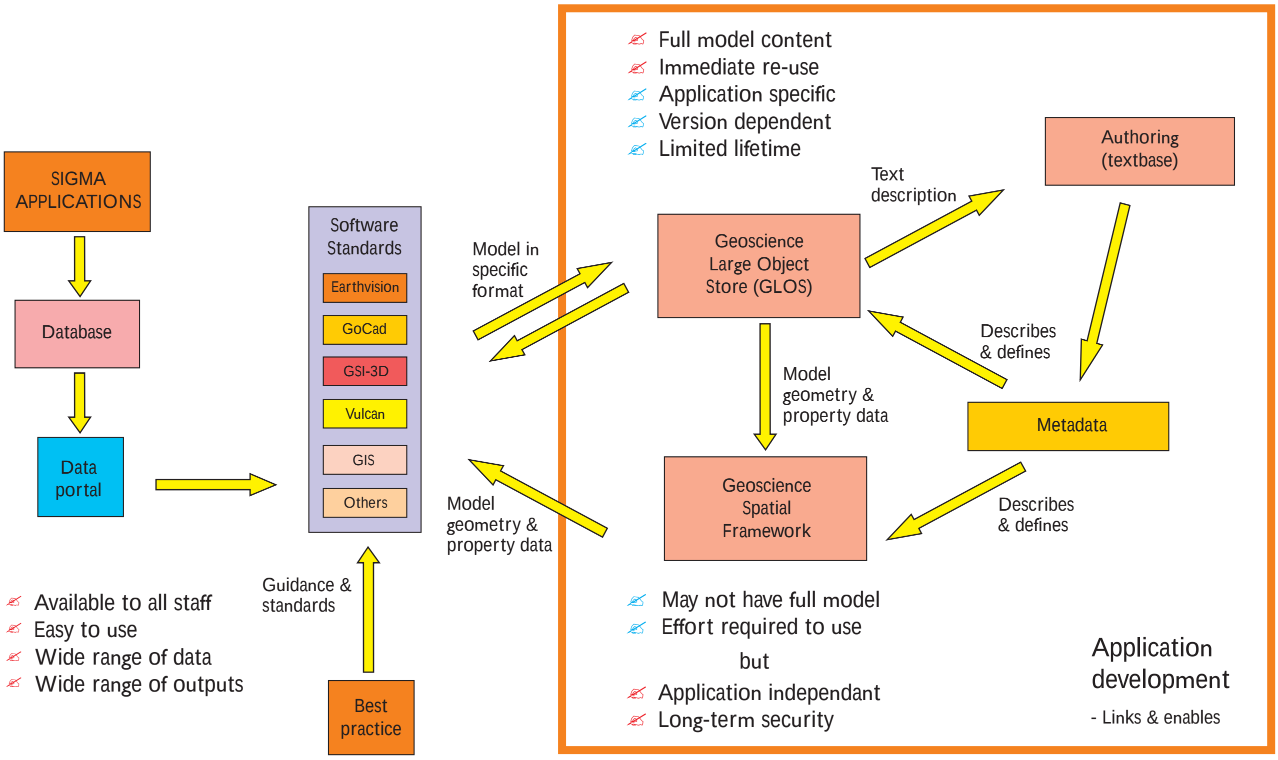
The DGSM framework allows users of models generated by the BGS to access the best interpretation of the concealed geology. It also allows them to be given enough information to evaluate that interpretation and to work in a user-friendly computer environment. The objectives for development of the framework were to ensure that the outputs from geoscientific modelling are secure, available and corporate. Those three adjectives conceal many interleaved considerations, each of which has been identified as a separate subproject and is described in the following sections. These cover developing corporate databases, writing applications that are easy to use and accessible, and establishing methodologies and protocols that are accepted, documented and available.

Across the BGS and the geoscientific community, models were being built that incorporated a broad appreciation of underlying observations and measurements, and the concepts that explained and integrated them. The starting point of the framework was the problem that these activities were not co-ordinated, and their outputs and accumulated knowledge were not being managed with a long-term view. To correct this, three over-riding principles were used in developing the framework. These were to:

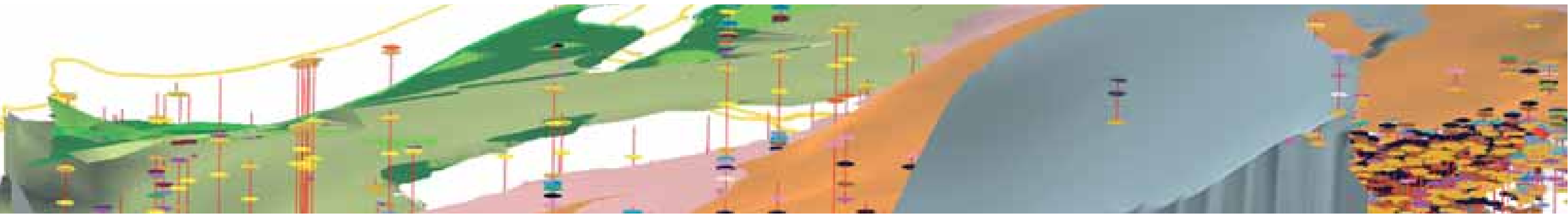
- build on corporate standards
- make developments that are extensible, so that they can be reused
- ensure that each subproject is related to the others and contributes to the framework as a whole.

The sections of the report are arranged so that the reader follows the logical process of building and storing a model.

Making it work



The flow of data through the DGSM framework.



THE DGSM FRAMEWORK

- *Data portal* — developed to give easy access to a wide range of 3D geoscientific data stored in BGS corporate databases
- *Software standards* — the corporate approach to modelling software
- *Geoscience large object store* — describes how model outputs can be stored in in their individual proprietary format
- *Geoscience spatial framework* — ensures that geometric form and geoscientific properties are shareable and preserved.

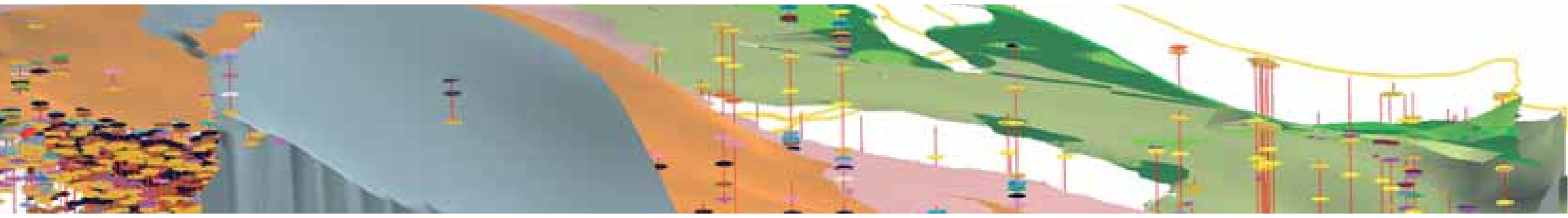
Scientific methodology requires that a process can be repeated and tested; in the case of systematic geoscientific modelling, this means that the user of the model should be told how the model was built and to be able to follow the procedure.

- *Best Practice* involves a description of how documented procedures are written and maintained.
- *Uncertainty* involves a mix of qualitative and quantitative methods that have been developed for scientists to describe the confidence or quality of their conclusions.
- *Authoring* involves methods for indexing text documents using keywords and providing efficient storage and retrieval of chosen topics.
- *Standardised metadata* has been developed, so that relevant models can be identified and evaluated, with their associated information.

All of these activities are linked and supported by a large number of computer software applications, ranging from web-based working environments, to specific programs for loading or extracting particular pieces of information. A training programme was developed to give a wide range of staff an overview of the systems and to raise a sufficient number of staff to expert level.

The SIGMA (System for Integrated Geospatial Mapping) project has developed methods for direct capture of multi-dimensional geoscience data in the field, for import to databases, and the subsequent creation of maps and model building.

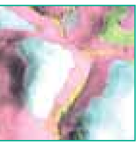
Making it work



Data portal

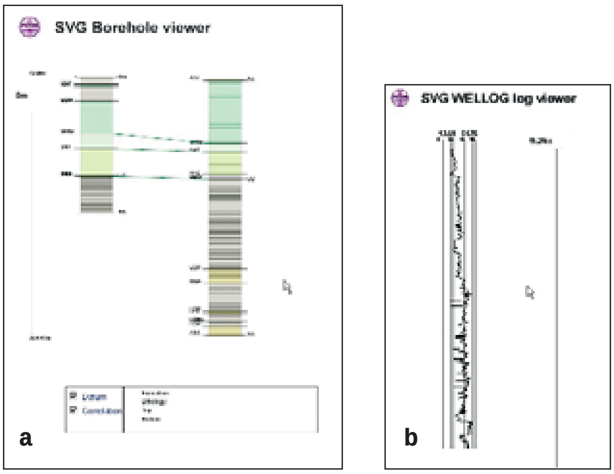
The DGSM data portal is designed to provide a vital bridge for modellers between corporate databases and the software packages used for 3D interpretation. The product is based around a user-friendly web-based GIS system that permits users to interrogate, preview and then download the data they require for modelling in a suitable format.

To achieve this objective, a primary task was to ascertain user requirements and prioritise the services available to staff. The following information sets were considered to be the most important and tackled as a priority:



- surface topography
- surface geology
- borehole geology
- geophysics
- seismic sections
- hydrogeology
- geotechnical.

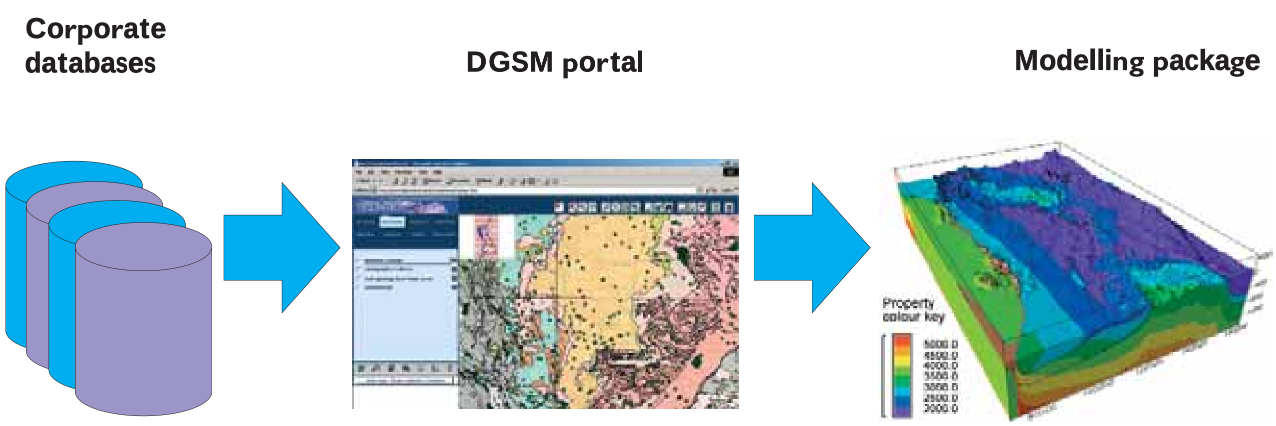
The information from these datasets was loaded into GIS layers so that the user could assess the quantity and quality of the digital data available. Pre-viewers were established allowing users to investigate the data in the third dimension, i.e. depth, via either cross-sections or a Java-based 3D application. The cross-section viewers are available for borehole and section information, while the 3D viewer can display all the information portrayed in the portal.



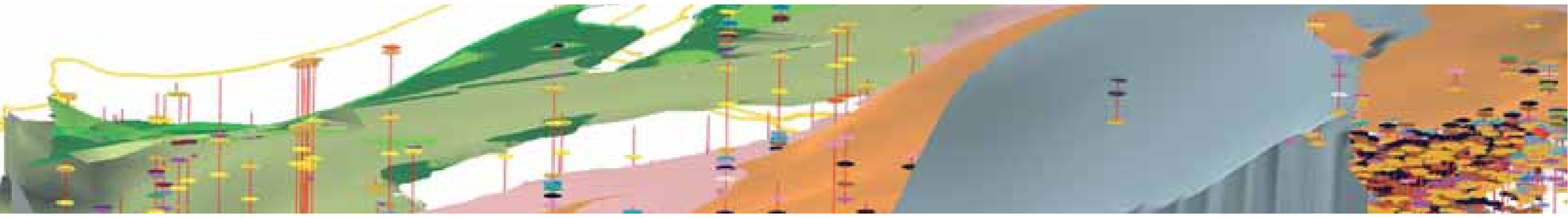
(a) *Linking boreholes into cross-sections (fence diagram).*

(b) *Extracting borehole geophysical logs.*

Easier access to 3D data



The portal gives an intuitive link between corporate data and modelling application.



Software standards

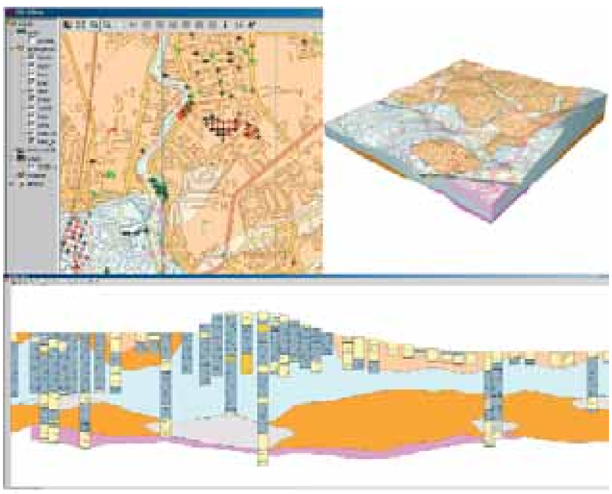
Geologists have always interpreted the Earth in 3D, but advances in technology have led to the proliferation of software packages, which allow this modelling process to be computer based. The BGS has used a number of these applications and needed to develop an informed strategy for supporting them. Consequently, we evaluated four packages: EarthVision™, GoCAD™, GSI3D™ and Vulcan™.

The modelling packages need to include functionality which allows the user to produce a satisfactory real-world model. One of the hardest of these tasks is the interpolation of models with sparse data. This relies on the geoscientist's deductive skills. To allow the interpreter to concentrate on the geoscientific issues, the package must also be user friendly by being well structured and easy to follow.

The project also reviewed several 3D viewing packages to establish their suitability for marketing finalised models via the Internet. The packages reviewed were Geoexpress, FracSIS and Java3D. The strengths and weaknesses of each product were addressed along with their suitability for use alongside current corporate applications. Each product has unique functionality as well as compatibility with other available packages.

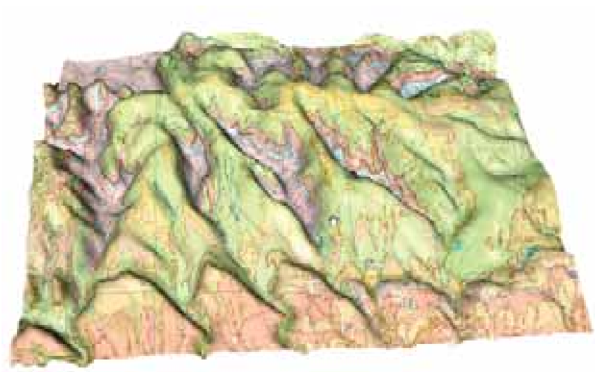
Modelling in 3D will continue to expand and develop within the BGS requiring more access to modelling applications. Access to multiple packages would be expensive, as well as unsustainable in terms of training and expertise. The study has enabled the BGS to focus, and prioritise maintenance and training, on a limited selection of packages. This does not exclude the continued use of others, where they fulfil particular modelling requirements.

3D geological model of the UK with 10 x vertical exaggeration. Purple layer = Moho, red/orange = granites, grey planes = major faults and white spheres are earthquake foci.



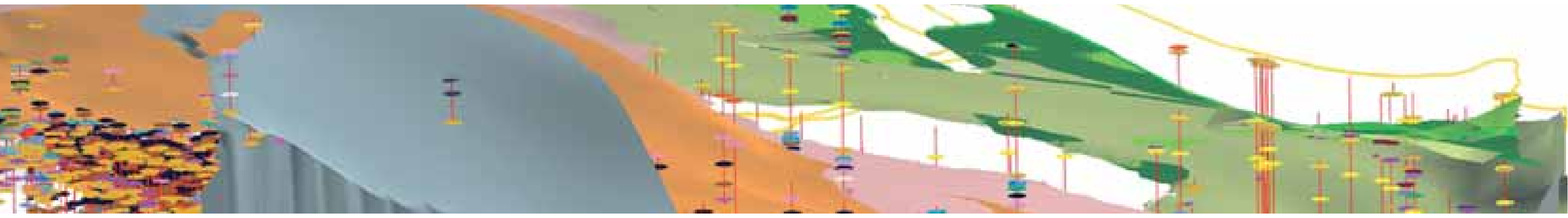
GSI3D™

Section and 3D map of the city of York at LithoFrame 10 resolution



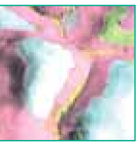
J3DPro™

Solid geology of part of the North York moors projected onto Nextmap dtm.



Geoscience large object store

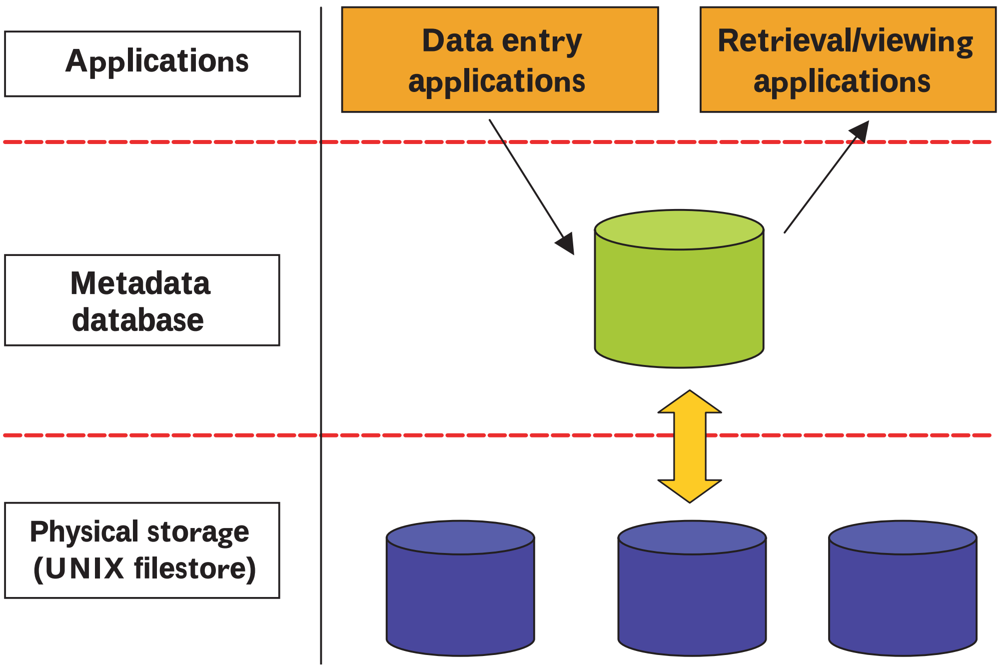
The aim of this project was to develop a corporate archive system for the digital representations of geoscientific models, which may include block models, modelled surfaces, fluid flow models etc. They will have been created using a variety of proprietary software including EarthVision™, GoCAD™, and GSI3D™ and many others. The geoscience large object store (GLOS) enables the full richness of the model (e.g. in terms of colour shading and annotations etc.) to be preserved and re-used. However, to make use of the models in the GLOS the user does have to have access to the original modelling software, which reduces the ability to share models. This becomes particularly relevant when supplying models to BGS clients. Another consequence of storing models in their proprietary file formats is that they may become incompatible with later releases of the modelling software. However, the GLOS system complements the GSF (Geoscience Spatial Framework) which holds models in a non-software specific format allowing them to be viewed independent of the original modelling software.

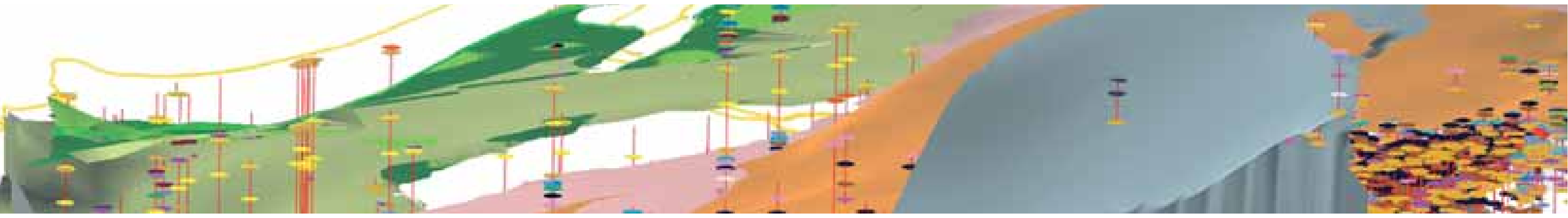


Whilst primarily concerned with the digital outputs from geoscientific modelling, the work has evaluated the potential for links between models and other related digital objects (for example, links to VRML visualisations of models, and also to images). VRML files can be created as exports from some proprietary modelling software (and from data in the GSF) allowing a model to be viewed in a web browser.

To achieve this, a system consisting of three main components has been developed.

- The GLOS file store is a secure repository for the physical storage of model files.
- The GLOS technical metadata database is linked to the GLOS file store, and contains the necessary information to allow a model to be retrieved from the GLOS and rendered in the original software. It is integrated with the BGS metadata system as a whole, facilitating easy searching and drill down to GLOS models from higher level metadata.
- A suite of software applications allows users to interact with the GLOS. This includes intranet-based forms for entering and maintaining the technical metadata about models, and Java-based software tools for efficient uploading of models to the GLOS, and downloading to the user's workstation. The GLOS applications are integrated fully within the DGSM workflow, and access to the system is controlled via a security management application, implemented as an additional Intranet web interface.





Geoscience spatial framework

A range of different modelling software packages is used to create models, each of which uses its own file formats and structure and are stored in the GLOS. From there they can be retrieved and re-worked in the software environment from which they were generated. These formats are often unique and sometimes cannot easily be decoded, so that data cannot easily be shared between applications or be read without the application that created it. The need for a shareable, secure, long-term repository for modelled data, led to the development of a data structure that was independent of the originating model software. It was recognised that this was likely to lead to some loss of information. A secondary objective was to allow models to be linked to attributes describing their properties and to enable the integration of DGSM models with other BGS datasets including metadata.

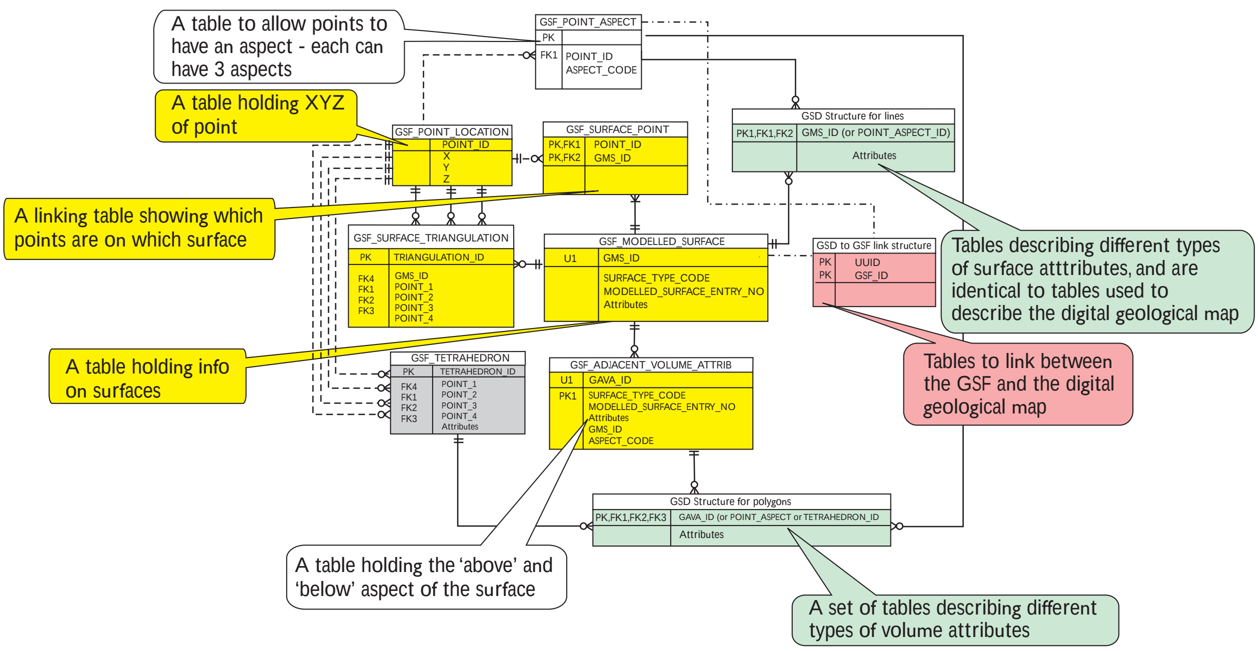
The geoscience spatial framework (GSF) was designed to meet these objectives. Its basis is the simplest possible spatial unit, the point, which is obtainable from the export formats of most modelling packages.

The GSF has been implemented in a relational database, with two key features. Firstly, because it is based on the point as the fundamental spatial unit, more complex spatial structures can be built by combining points. Thus triangles and surfaces can be defined in terms of collections of points, and more complex structures such as tetrahedra, required for some types of model, can be built as well.

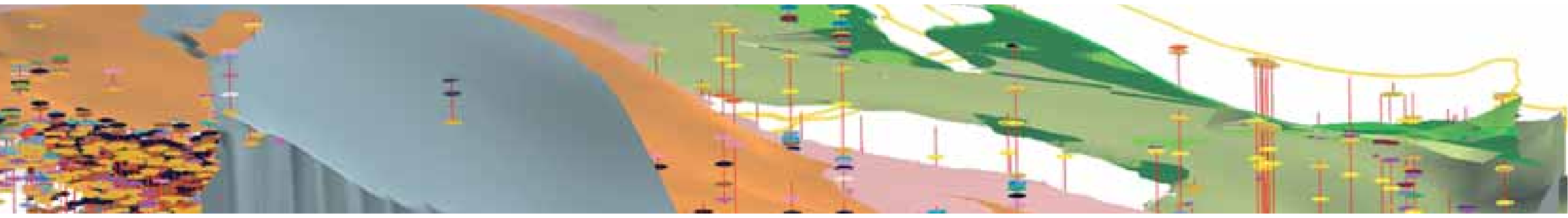
The second feature of the GSF is that it allows attribute tables, like those used in GIS systems, to be attached to any of the defined spatial entities. It also links points and surfaces to the DGSM metadata to enable metadata-based retrieval.

The majority of models in the DGSM are of surfaces and therefore the points held in the GSF lie on surfaces, with volumes implied between these surfaces. In order to enable attributes to be attached to the intervening volumes the concept of 'aspect' has been introduced. Each point can have up to three aspects, ‘at’, ‘above’, and ‘below’. The ‘at’ aspect links to attributes describing the surface, while the ‘above’ and ‘below’ aspects can be linked to attributes describing the volumes either side of the surface.

The design of the GSF also allows for the linking of lines or areas in a GIS to their equivalent surfaces or volumes in the DGSM, using the ‘GSD to GSF link structure’.

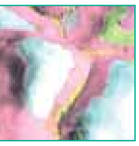


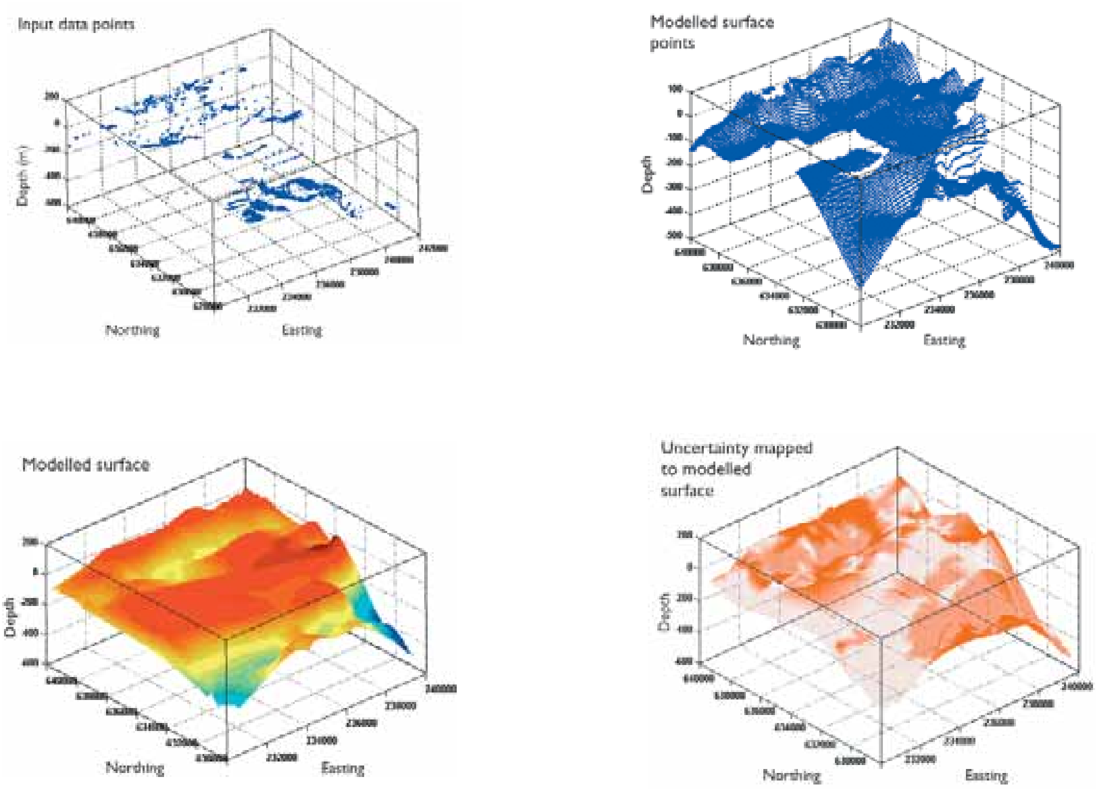
How we exchange model data



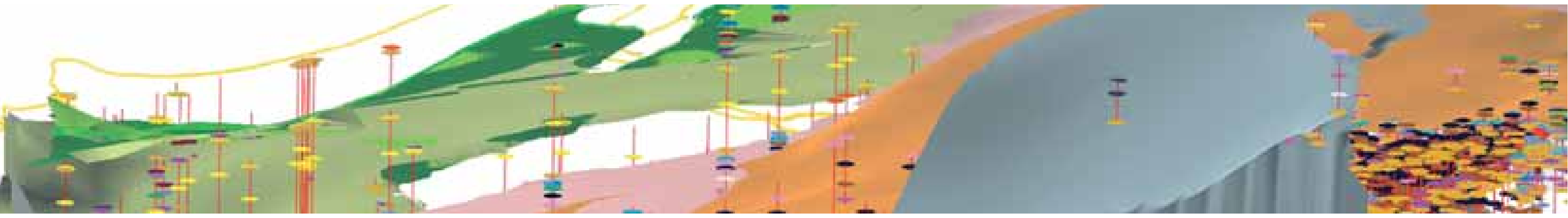
Uncertainty

The aim of this work was to investigate methodologies for characterising and quantifying uncertainty in the geoscientific models we produce. Such a procedure needs to be applicable to a variety of modelling scenarios and encompass a project-level workflow that is not too complex yet thoroughly addresses the sources of uncertainty found in each modelling process. The methodology is illustrated here using a dataset from the DGSM Midland Valley population project. A surface model, built in EarthVision™, from a variety of point-depth data sources (borehole, cropline, etc.) for the Ayr Hard Coal Seam was used. Initially work was done using an iterative statistical technique to investigate what effect the use of different subsamples of the original data had on the surface generated by the modelling software. Following on from this initial work we looked at ways in which we could elicit qualitative information about how the model was built from the geological and technical experts who built it. We had considerable success employing a technique called 'cause and effect analysis', where a diagram (Ishikawa, or 'fish' diagram) is drawn manually during a brainstorming session to catalogue and understand the sources of uncertainty feeding into the modelling process. Each input was then characterised in a fuzzy logic system, a way of formalising linguistic input, using membership functions that allow the modeller to use terms such as good, bad, high, medium and low. To connect these inputs, the modellers were then asked to formulate a set of rules that characterised the system.

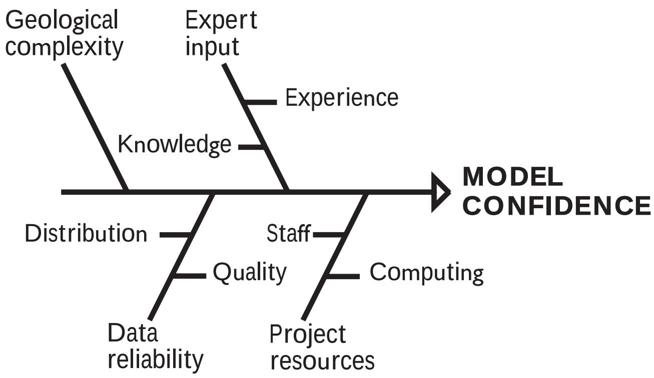


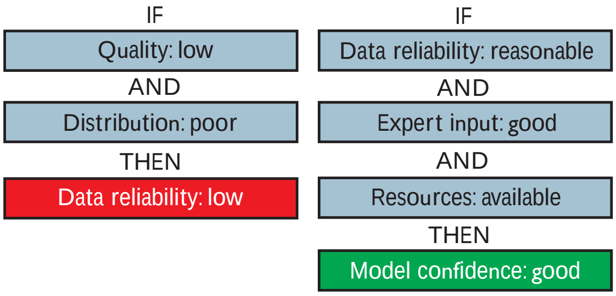


The sequence for determining uncertainty for the Top Hard Coal in the Midland Valley of Scotland.



Uncertainty





(Above) *Simple Ishikawa (fish) diagram.* (Right) *Fuzzy logic rule set.*

Each data point in the model is processed by the fuzzy system to produce an overall uncertainty model which can be mapped back to the original surface to show areas of higher uncertainty using colour depth.

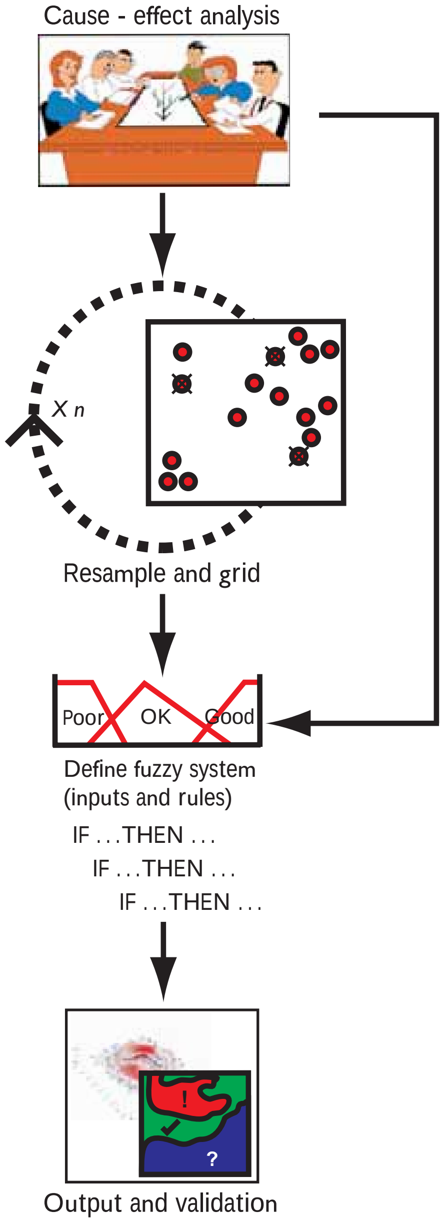
The culmination of the study is a workflow to be used by modelling projects shown in the diagram.

1 Assess the factors feeding into the modelling project using cause and effect analysis, producing an Ishikawa diagram.

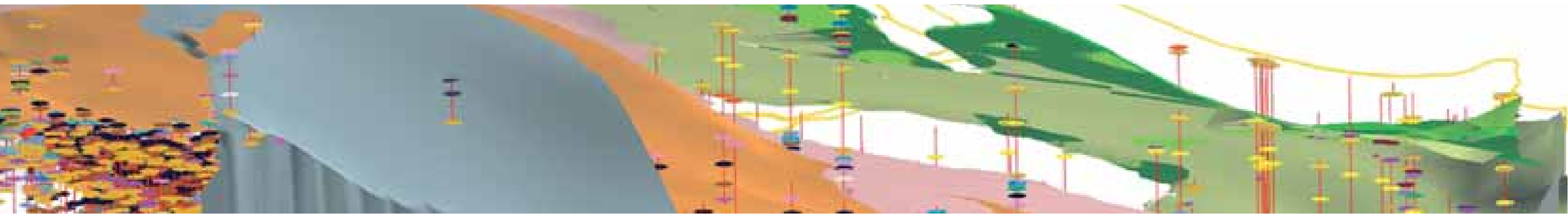
2 Undertake the iterative surface generation, using modelling software that interpolates surfaces in an automated fashion (if relevant).

3 Pass each data point through the fuzzy system to be characterised, and test against the rules to arrive at its uncertainty classification.

4 Transform the fuzzy, linguistic classification into a numerical output which can be used to visualise the uncertainty across the model.



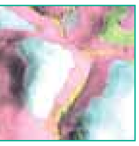
What is the quality of our models?

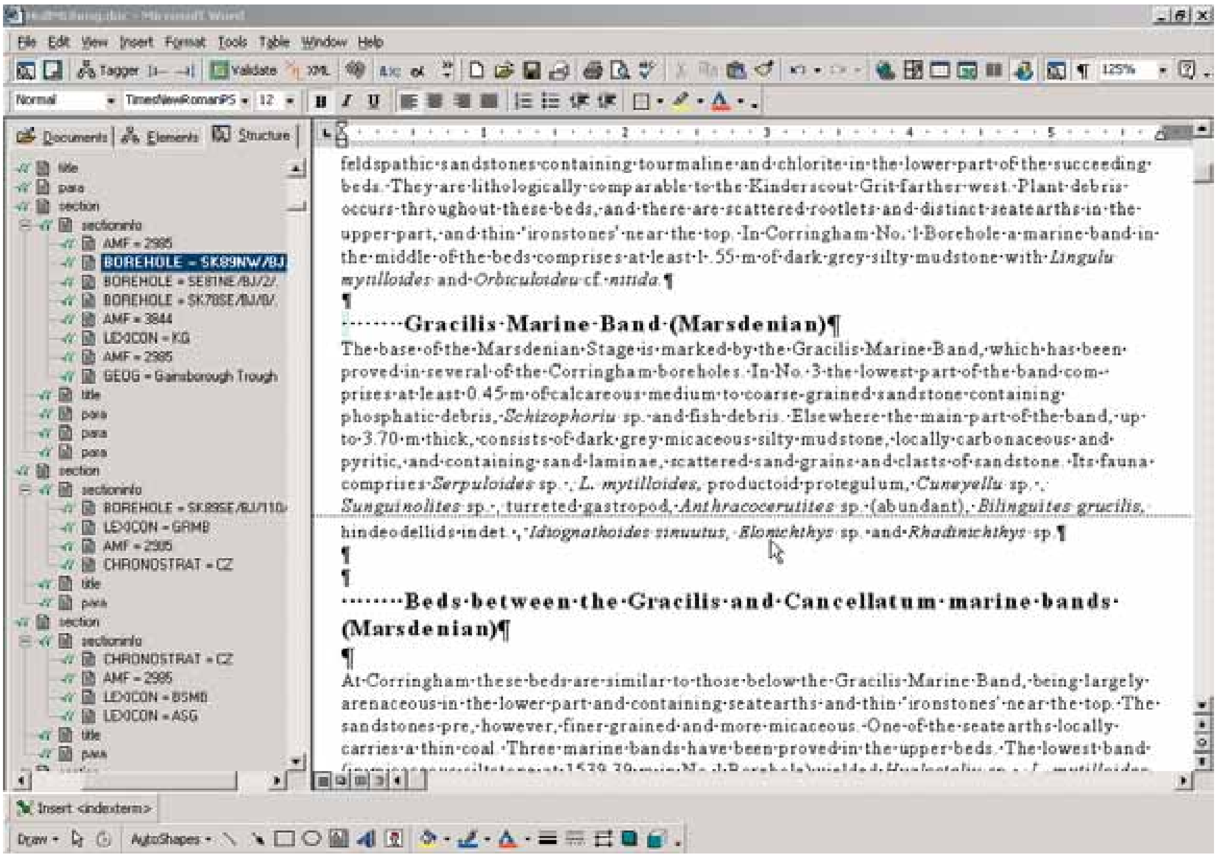


Authoring

The authoring project was established to develop standards for storing texts (and associated figures, plates, references etc.) that are part of our geoscientific knowledge. We developed a system that marks-up texts using Extensible Mark-up Language (XML), which is a structuring framework for text and numeric data that conforms to WWW standards. It involves tagging or placing the digital text within specified elements, which enhances the way that data can be stored, retrieved and transmitted for example, over the WWW. For instance, a paragraph of text would be placed between the paragraph tags <para> and </para>. A fragment of such mark-up is shown in the text box *(right)*.

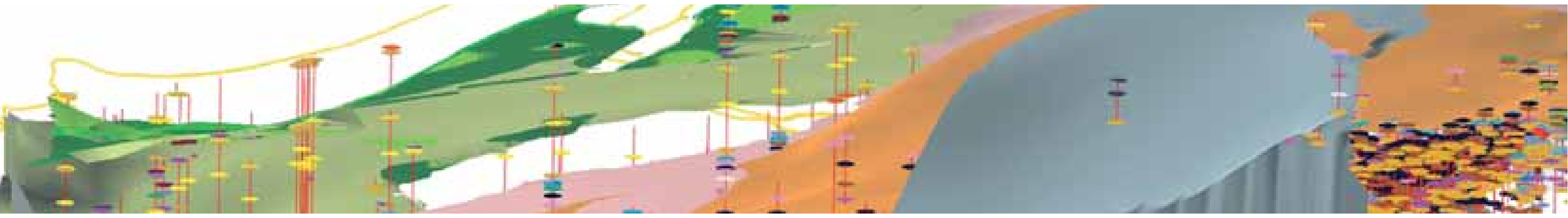
```
<para>
  <parainfo>
  <indexterm scheme="RCS"value="LAVA"/>
 </parainfo>
Top Paleogene lavas The Top 'Paleogene lavas surface
penetrated in well 163/6-1A (<link linkend="f016"
type="figref">Fig. 16</link>) forms a regionally strong
reflection that can be mapped over the entire study
area (Appendix 1, Map 3). The absolute ages of the
lavas within the study area are not known, but they
are ascribed a Paleogene age on the basis of NE
Atlantic regional studies (e.g. Ritchie et al., 1999b).
</para>
```





Using Microsoft Word with XML facility to mark up geological text with links to borehole, chronostratigraphy, lexicon and geological thesaurus databases.

Describing our models

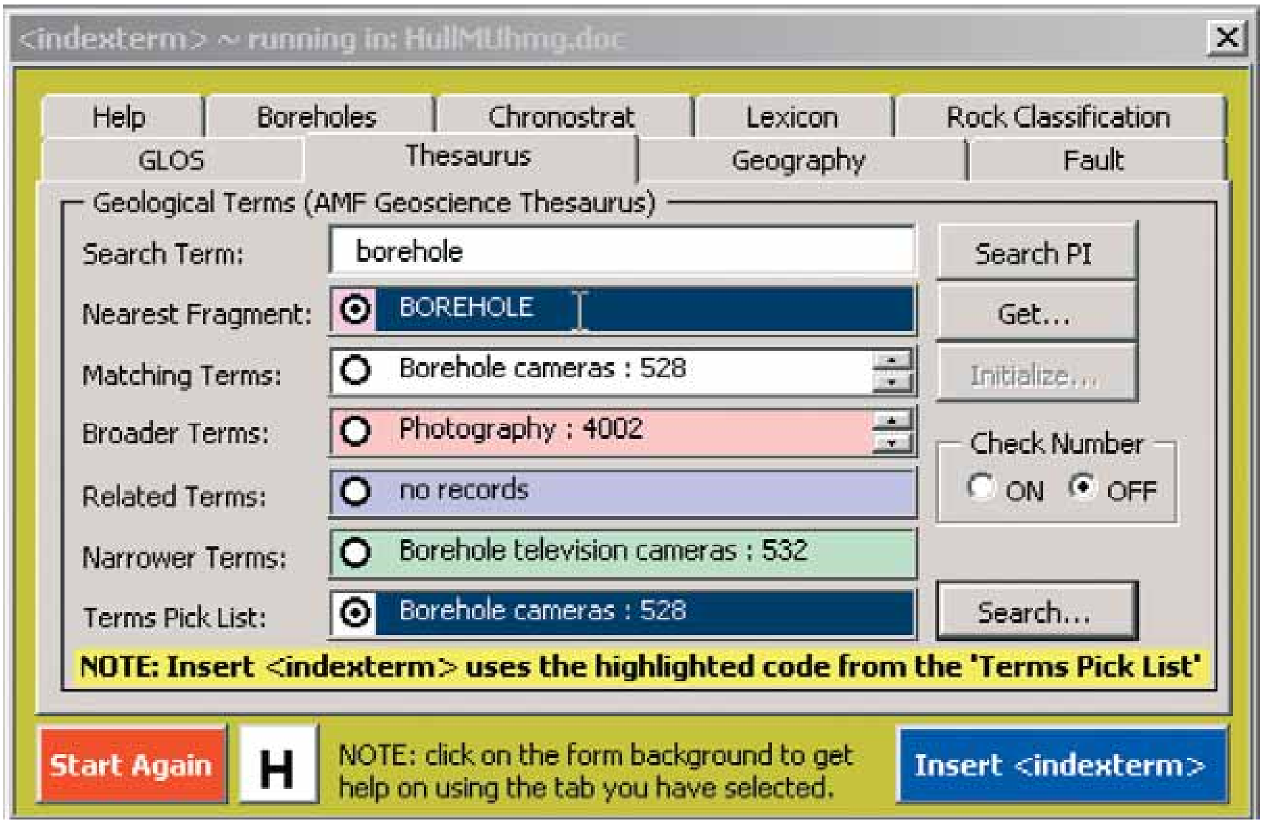


Authoring

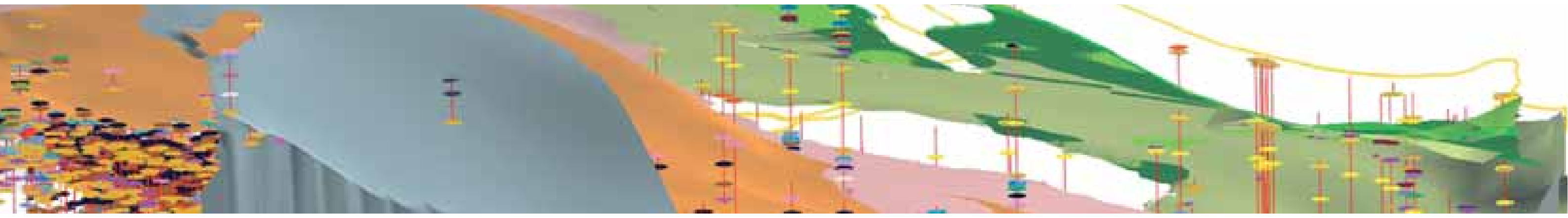
Firstly these tags indicate what part of the document the tagged section represents, e.g. Chapter 1, Chapter 3, appendices, figures, plates, paragraphs etc. (termed structural mark-up). Secondly, they contain attribute or indexterm information, e.g. the formation, stage, group etc. that the paragraph is describing (termed content mark-up). Indexterms are used to search the documents to retrieve fragments that refer to items of particular geoscientific interest.

Tagging is done in MS-WORD 2000, using an add-on called WORXse by Xyvision and a BGS-written indexterm tool, which allows an author to select indexterms. A document in the process of being marked up is shown below. Once marked up and entered into the ORACLE text database, sophisticated queries can be made to bring back any items of interest to the searcher in web query interfaces.

A spin-off of this research has been its involvement with international collaboration to develop a generic geoscientific standard of agreed elements defined in an XML schema called GeoSciML (GeoScientific Mark-up Language).

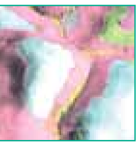


The indexterm tool allows text to be marked up for types of geoscientific topic covered by BGS standard dictionaries as shown on the tabs.



Metadata

Metadata can be defined as the information and documentation that makes data understandable, shareable and usable by users over time. In the context of the DGSM the term data can be extended to include models. The purpose of metadata is therefore to answer questions posed by potential users of the data or models to enable them to determine if the data or models will be of use to them. A first step in defining what metadata is required is therefore to define the types of question to be asked. For the DGSM three types of question were identified.



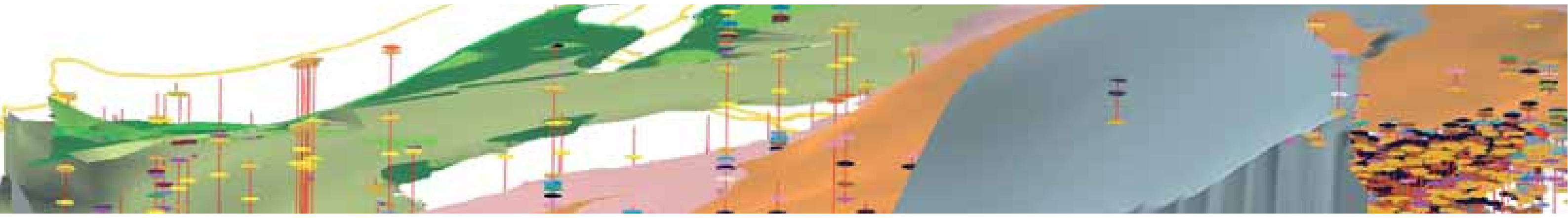
- People building models want to know what suitable data exists for input to their models, including what data was used to build similar models previously.
- People using models want to know what type of models already exist in particular areas.
- More advanced users of models want to know what the models were based on and how they were developed from the data.

The DGSM metadata was developed to enable these types of question to be answered and led to a requirement for three types of metadata which were termed ‘data’, ‘model’ and ‘inference’ metadata.

The ‘data’ metadata describes the data subset used to create a particular model. This includes information about the parent dataset from which it was derived, descriptive information including keywords and an abstract, the location, and importantly how the data subset was derived from the full dataset. This last item includes the criteria for including or excluding data items.

The ‘model’ metadata is simpler and provides information describing the model, its location in 3D space, the purpose for which the model was created and the fitness for that purpose, along with a description of the scientific concepts underlying the model. ‘Inference’ metadata describes how particular data was interpreted and interpolated to create a specific model, and the quality of the data for this purpose.

The metadata population application.



Metadata

less specific/broader terms [+] *(n)* is number of results including narrower+related

Geology (374) >> Petrology (59) >> Igneous petrology (7) >> Volcanic rocks (7)
Geology (374) >> Petrology (59) >> Igneous petrology (7) >> Basic igneous rocks (0)

subject term click to select	related terms	more specific/narrower terms	jump to root terms
Basalt	Dolerite	+ indicates another level of narrower terms, *(n)* is number of results	Energy
	Gabbro	Alkali basalt + (0)	Engineering geology
	Keratophyre	Analcime basalt (0)	Environmental science
notes	Latite	Analcimite (0)	Geochemistry
0 results	Leucitite	Andesine basalt (0)	Geology
0 including narrower+related	Limburgite	Flood basalt (0)	Geophysics
used for	Nephelinite	Leucite basalt (0)	Hydrology
Spilite	Oceanic crust	Melilite basalt (0)	Land use planning
	Shoshonite	Nepheline basalt (0)	Mineral deposits
	Tachylite	Olivine basalt (0)	Mining
	Ultrabasic rocks	Picrite basalt (0)	Natural hazards
		Quartz basalt (0)	Natural resources
		Tholelite (0)	Remote sensing
			Solid earth geophysics
			Stratigraphy
			Surveys

The geoscience thesaurus.

In order to be useful, metadata should describe data in a uniform way to enable comparisons to be made and data searches to be carried out consistently. Metadata standards are, therefore, important and recently an international standard, ISO 19115, has been agreed. This was adopted for the DGSM and all three types of metadata were mapped on to the ISO standard, and implemented in a relational database.

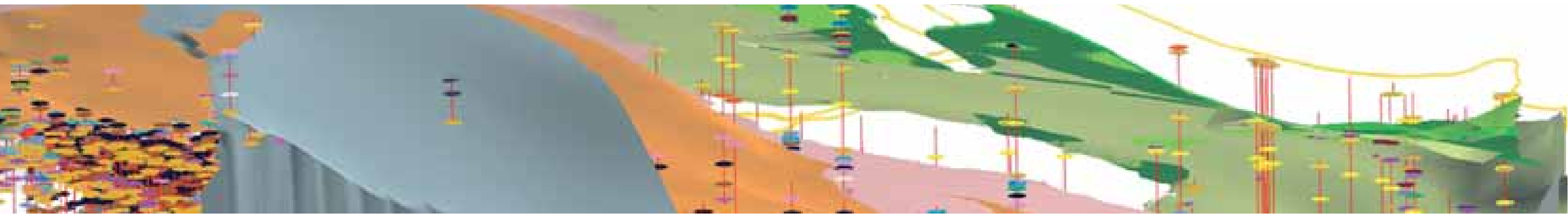
An application has been built to enable the metadatabase to be populated and updated. This incorporates 'help' information describing each metadata field and constrains fields using dictionary values where appropriate. The population of different elements of the metadata takes place at various stages in the model-building process and the metadata-population application has been fully integrated into the DGSM workflow to enable this.

Geoscience thesauri

Metadata keywords provide a simple way of describing or finding a model or dataset. However they can only achieve this if they are drawn from a common list used by both the person describing the model or dataset and the person using the metadata to find a model or dataset.

Keyword lists are even more useful if they are ordered as structured hierarchies or thesaurii. Such a hierarchy might have at its top level a term such as 'rocks', which could be sub-divided at a lower level into 'igneous', 'metamorphic', and 'sedimentary', which in turn could be further sub-divided into the types of each class of rock. The advantage of this approach is that the person using the metadata for searching doesn't need to know the exact term used to describe a model or dataset. For example a geologist may have described a model with the term 'alkali basalt' whereas a person searching wants all models of 'basic igneous rocks'. Because the term 'alkali basalt' lies beneath the term 'basic igneous rocks' in the thesaurus hierarchy a model described with the keyword 'alkali basalt' would be retrieved against a search for 'basic igneous rocks'.

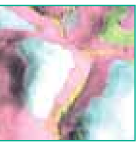
A review of geoscience thesauri concluded that the Australian Mineral Foundation (AMF) thesaurus was the most appropriate for use by the DGSM. This thesaurus was used to populate keywords in the DGSM metadata and an application was written that allows the thesaurus hierarchy to be explored and appropriate terms selected. The figure shows the thesaurus application with the term 'basalt' selected. Along the top are the two possible hierarchical paths down from the term 'geology', one via 'volcanic rocks' and the other via 'basic igneous rocks'. The application also lists related terms, such as 'dolerite', and more detailed terms such as 'alkali basalt'. This provides a rich environment for selecting terms to describe or retrieve models.

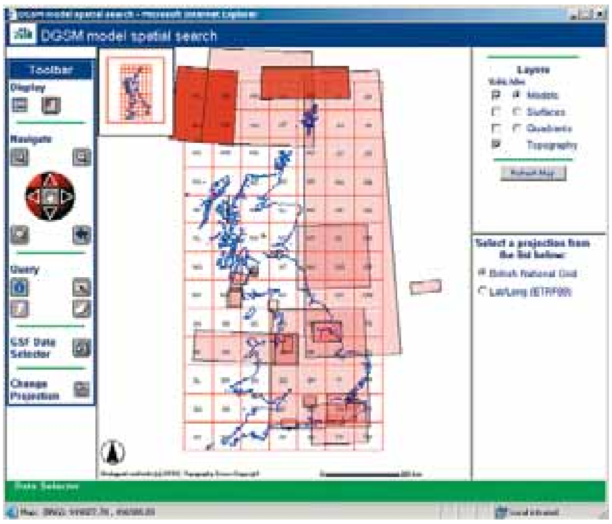


Development of applications

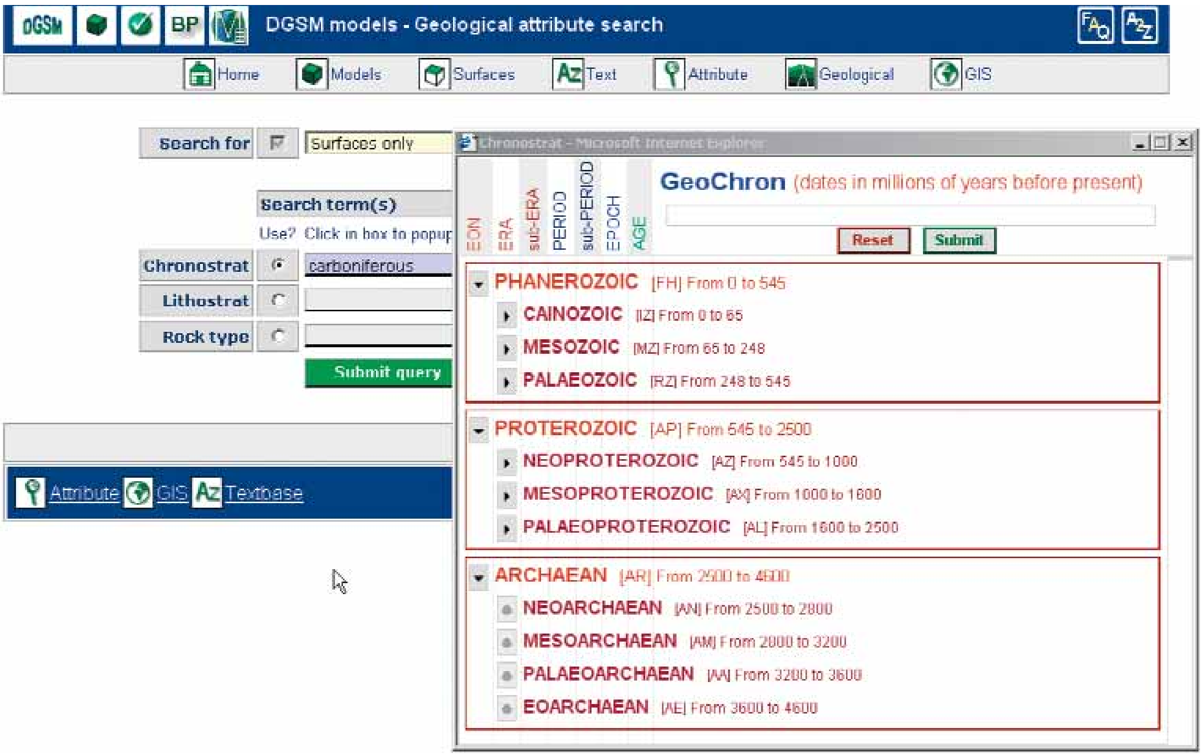
The development of applications project was responsible for bringing the DGSM to life; facilitating modelling activities, capturing their results and making them widely available. Building on foundations laid by other DGSM framework projects, an infrastructure was required that allowed users to create models in compliance with DGSM standards and methodologies. These models needed to be stored, and subsequently retrieved, along with detailed information about the models, the data that was used to create them, the thinking behind the building of the models and the conclusions that were drawn from the modelling. In short, it was required to provide access to the BGS's knowledge on UK geoscience.

Applications developed include attribute and spatial search interfaces for retrieving DGSM models *(right and below)*. These give access to a model viewer, enabling the user to view and analyse a retrieved model, obtain details of that model, link to related models, download the original model files and export data extracted from the model in various spatial reference systems and modelling formats.

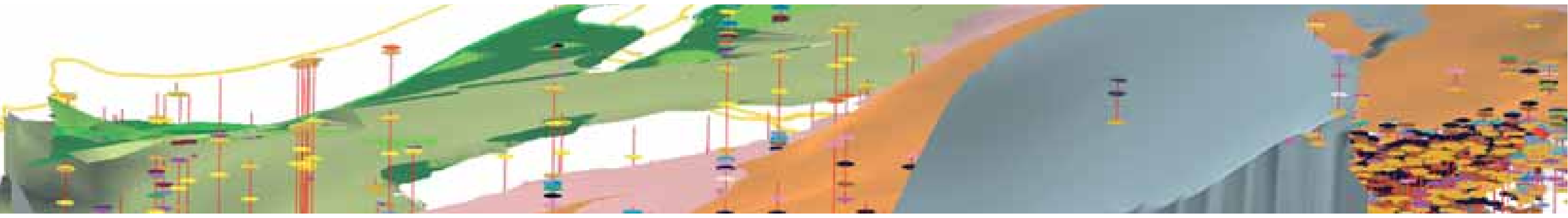




The distribution of DGSM models across the UK displayed in the spatial model browser.



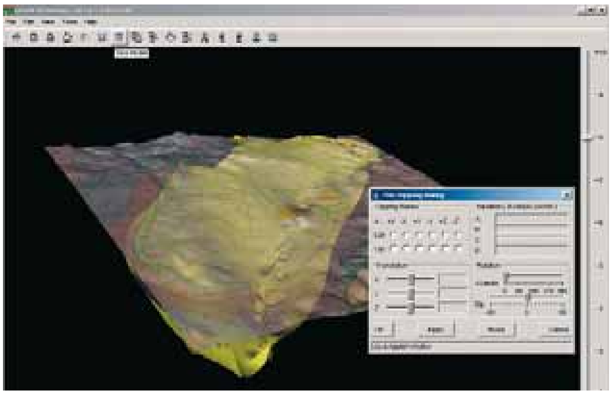
A search for surfaces modelling the Carboniferous, using the chronostratigraphy browser.



Development of applications

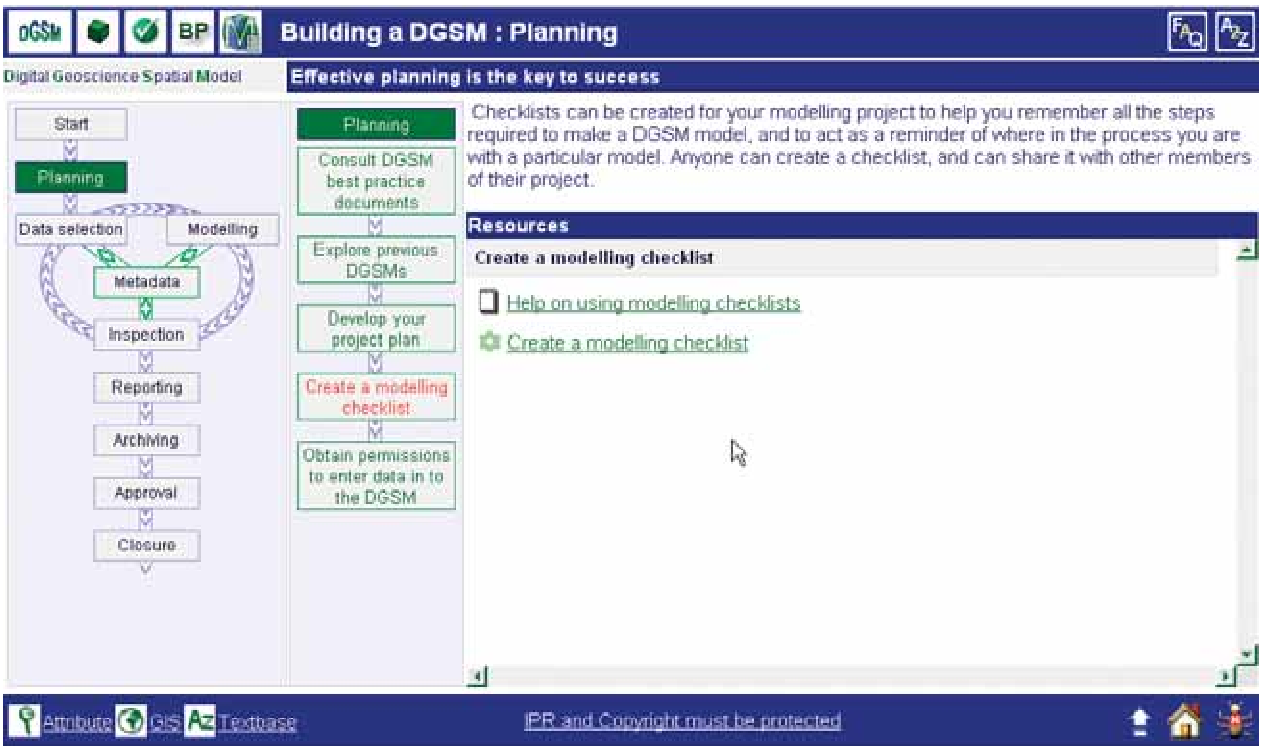
A 3D model viewer has been developed to enable any user to examine a model without the need for licensed modelling software. It also facilitates basic model analysis techniques such as drilling virtual boreholes and taking cross-sections. Another suite of applications has been developed to load models into the corporate store. They also capture information that describes the models and assists in their subsequent retrieval.

These applications are presented to BGS staff via a workflow that conducts the user through the process of building a DGSM model to BGS standards, allowing them to keep a commented checklist for QA of the steps they have undertaken *(below)*. The applications are further supported by best practice and other documentation that assist modellers in the safe passage through the various stages of the flow.

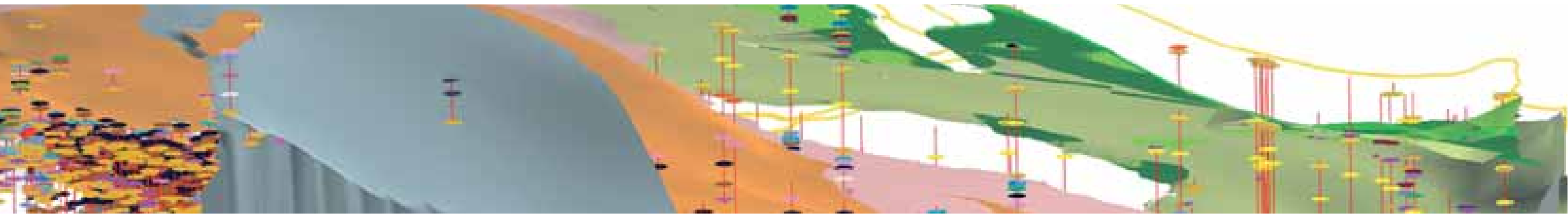


The 3D model visualisation tool showing the base of the Jurassic modelled in the Cheshire Basin with overlying topography.

The applications have been developed in discrete modules, allowing them to be easily repackaged for different audiences. Currently all applications are available internally to BGS staff. In the future, free public access to some of these applications and the data they deliver could be made available via the BGS internet site. Access to more detailed information could be made available as a subscription service on an extranet site.

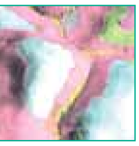


The DGSM modelling workflow highlighting the steps involved in the planning stage.



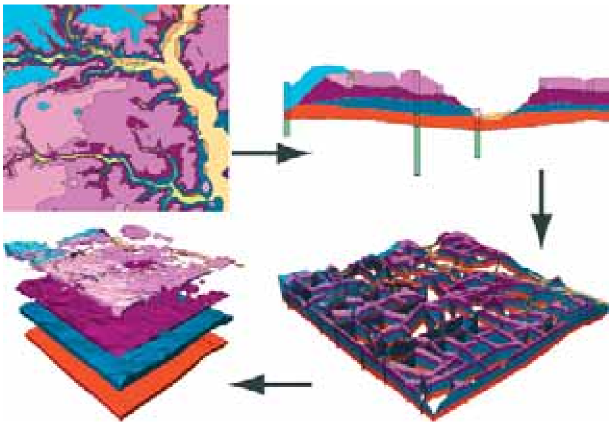
SIGMA

Increasing use of information and communications technology for managing and delivering geoscientific information is driving the development of digital methods for geological data visualisation, recording and interpretation in both 2D and 3D. The BGS SIGMA project (system for integrated geospatial mapping) is updating geological survey methods to harness these rapidly developing innovations.



Digital tools for data collation, field data recording, remote sensing interpretation, borehole logging, and digital geological map compilation have been successfully implemented in BGS projects over the past 15 years. The challenge has remained, however, to streamline these technologies and link them seamlessly into an integrated digital survey system backed by common data standards. SIGMA has therefore defined and documented an underpinning framework of best practice for survey and information management, which has then informed the design brief and specifications for an integrated GIS-based toolkit. This toolkit enables assembly and interrogation of existing geological information, capture of new data and geological interpretations, and delivery of 3D digital products and services.

Digital data capture in the field.

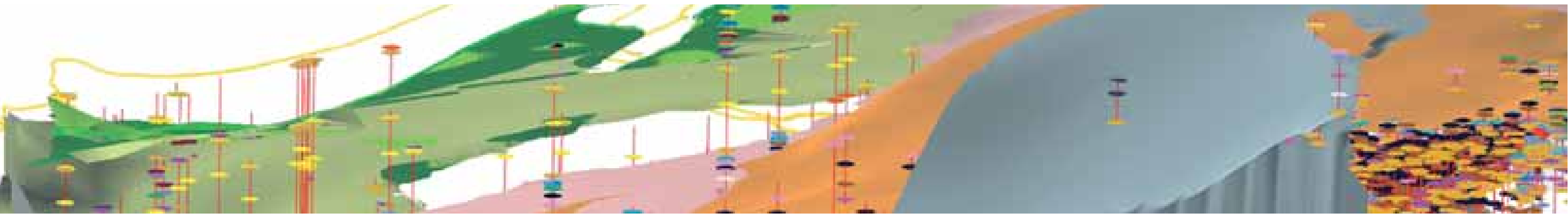


Geological map cubes — DiGMap3D systematic survey output for the 21st century.

Implementation of SIGMA has required definition of data models and standards, re-engineering of work processes and management systems, and the introduction of new training. The SIGMA toolkit itself uses commercially available hardware and software. Customisation has been kept at a minimum to limit future upgrade costs and reduce reliance on individual suppliers.

Implementation of a fully digital workflow for 3D geological surveying (see right hand page) has been a key objective of SIGMA. The workflow and associated tools enable review of existing geological interpretations in desktop GIS, digital data capture in the field, compilation of new maps and GIS, and construction of 3D models.

Ongoing development and refinement aims for a seamless system with implementation of wireless technology for integration of office and field work environments.



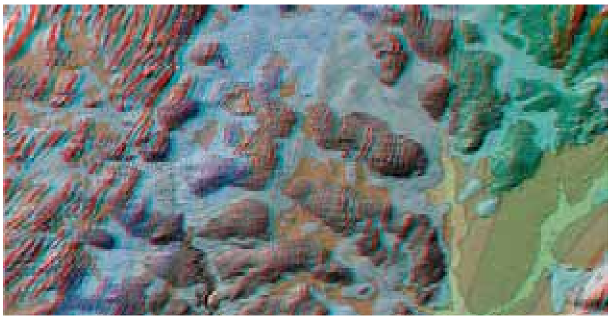
SIGMA

Pre-fieldwork desk study. Existing geological mapping is digitised and overlain onto digital terrain models and aerial photography. New interpretations are added and targets for field survey and checking are identified.

Digital field data collection. New field data is captured digitally using 'ruggedised' pocket and tablet PCs, and includes refinements to the geological interpretation and additional information on environmental hazards and resources.

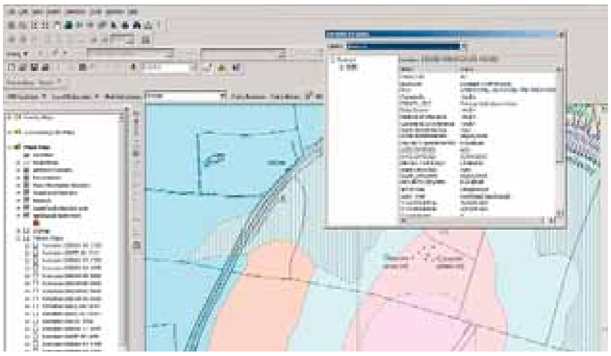
GIS compilation. The new geological interpretation is compiled and validated at the field base and HQ using GIS software on laptops and desktop PCs. The GIS is attributed with geological, hazard and resource information.

Digital 3D modelling. The GIS is cross-validated with subsurface data, and integrated 3D geological models are constructed. Maps, GIS, profiles, and various predictive outputs can be generated directly on demand from the model and from its supporting databases.

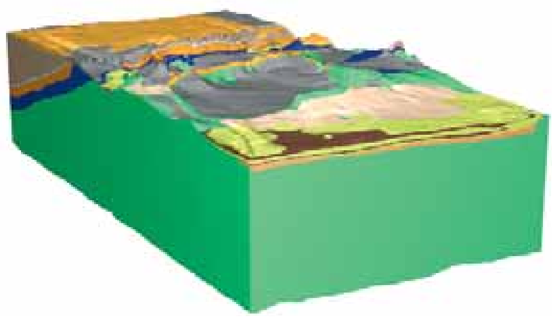


Geological map draped on digital terrain model, central Wales.

Tablet PC and GIS software are used for digital field data capture.

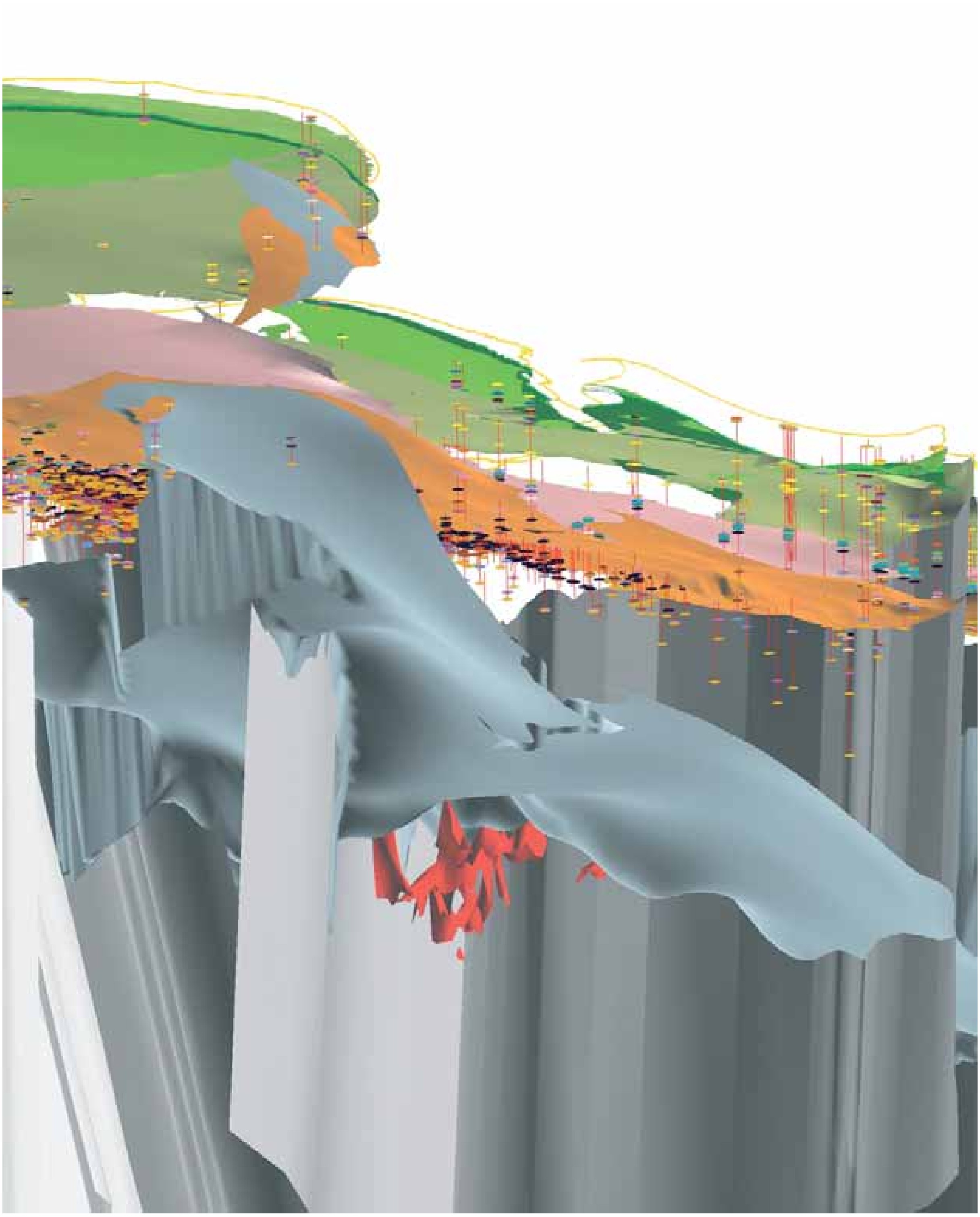


Digital geological map compilation, north-east England.



Digital 3D models — geological building blocks of the UK.

POPULATION PROJECTS



POPULATION PROJECTS

DGSM framework projects have been developing databases, standards and applications, and a range of models have been built to represent the many different faces of British geology. However, different geological environments require a variety of approaches to the creation of representative models so there is a need to document best practice for each environment. This was the main objective for the population projects.

Our plan was to join with established modelling projects to build on experience. These included projects on the Quaternary succession of the Humber Estuary; The Tertiary model of London Underground (LOCUS); the Permo-Triassic Cheshire Basin (based mainly on reflection seismic survey data); the Midland Valley of Scotland (predominantly Coal Measures base on boreholes, mine plans and geological linework); and the Atlantic Margin (a potential oil province that has been the subject of many regional geological syntheses and 2D seismic surveys). They covered a range of geological ages, user interests and data types and tested the framework studies with different approaches to modelling.

Getting started

We started work by pulling all the low-resolution models together to build a complete model for the UK down to the deepest layers of the crust. A further model for the area around the BGS headquarters focussing on the Nottingham and Melton geological map sheets was developed based on modern geological linework, high-quality seismic reflection data and boreholes.

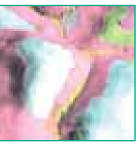
The complex Lower Palaeozoic geology of the Lake District and mid-Wales and the Precambrian of the Scottish Highlands each provided differing styles of complexity, ranging from faulted volcanic rocks in a massive caldera, to heavily faulted and folded turbidite successions and overfolded nappes respectively. We expected these examples to pose challenging problems.

In order to relate modelling to geological resources, we instigated projects to investigate sand and gravel deposits in East Anglia, to examine hydrogeological process modelling and the hydrogeological character of the Permo-Triassic basins of the West Midlands.

The DigMapGB enhancement project underpinned each of these projects. It provided digital geological linework attributed with elevation and organised as coherent geological lines plus digitised and validated geological cross-sections and generalised vertical sections from published geological maps.

DiGMapGB enhancement

DiGMapGB is a dataset of the digitised linework and output polygons that comprise a geological map, together with their lithostratigraphic and rock-type attribution. The BGS has comprehensive coverage of the UK at a range of scales. These data are a most important contribution to modelling the subsurface. In order to condition the data for modelling, work initially concentrated on adding elevation values to the linework by draping layers of geology onto terrain models, and converting the map marginalia into 3D data, in particular the geological cross-sections drawn on maps.



The attributes of the surface DiGMapGB polygon data can be interrogated and extracted from the dataset as a linear representation of bases or tops of various geological units. The 'z' values of elevation are easily captured within ESRI ArcView™ and presented in either ASCII text files or ESRI 3D shapefile format. After testing and proving the methodology, it was decided that this process was best left until the actual time of modelling projects, due to the regular updates of DiGMapGB-50 and the use of different terrain models in different circumstances, in order to obtain the most suitable 3D linework for the particular project.

The second major product from this project has seen the digital acquisition of horizontal cross-sections from the 1:50 000 printed geological maps transformed into 3D vector form. The geological formations have been described using the same standard attribution as the surface DiGMap data, those values at subsurface, where necessary, have been derived by referencing the

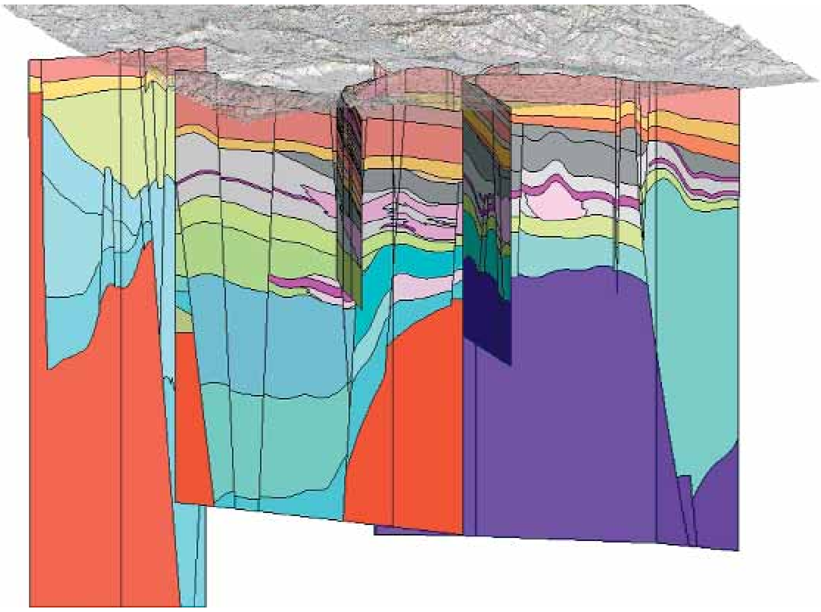
DiGMapGB data draped over terrain model with vertical exaggeration.

DiGMapGB enhancement

generalised vertical sections printed on the map by experienced cartographic staff consulting the Lexicon. Output polygon data and individual fault lines have been provided as ASCII text files and ESRI 3D shapefiles. These are made available from the Data Portal and can be converted into other appropriate formats for corporate modelling applications. They are also loaded to the SAN 'S' drive.

Another skill used to good effect, especially with our many visitors, is the ability to produce fly-through movies of areas of interest using ArcScene and a software extension called MapAnimator, to show DiGMapGB and cross-section data in 3D. Engineers, geologists and the general public find the moving images exciting, the third dimension bringing more realism and understanding to their knowledge of geology: it's no longer just a coloured area on a flat map.

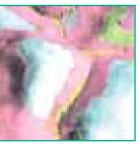
Example image of extracted top or base of particular geological unit at surface — base of the Mercia Mudstone Group from the Nottingham Sheet (126) is highlighted.



Polygonal cross-section data shown beneath a draped surface layer. The data contains attribution based on DiGMapGB 'lex-rock' values. A layer of separate fault lines is also available for use by modellers and scientists.

South-east England

This project was undertaken to define strategies for the modelling of the Mesozoic 3D geology in south-east England at 1:50 000 and 1:250 000 scales, and to ensure that any problems encountered in the building of the models informed the development of the DGSM framework. Models were created using a variety of data sources, including surface geological maps, boreholes and seismic data and all but one of the nine tasks focussed on the Chalk, an important aquifer in the region. The model of the Weald area tested the building of 3D models of the entire Mesozoic succession from legacy 2D structural maps and integrated borehole information that postdated the generation of the maps.

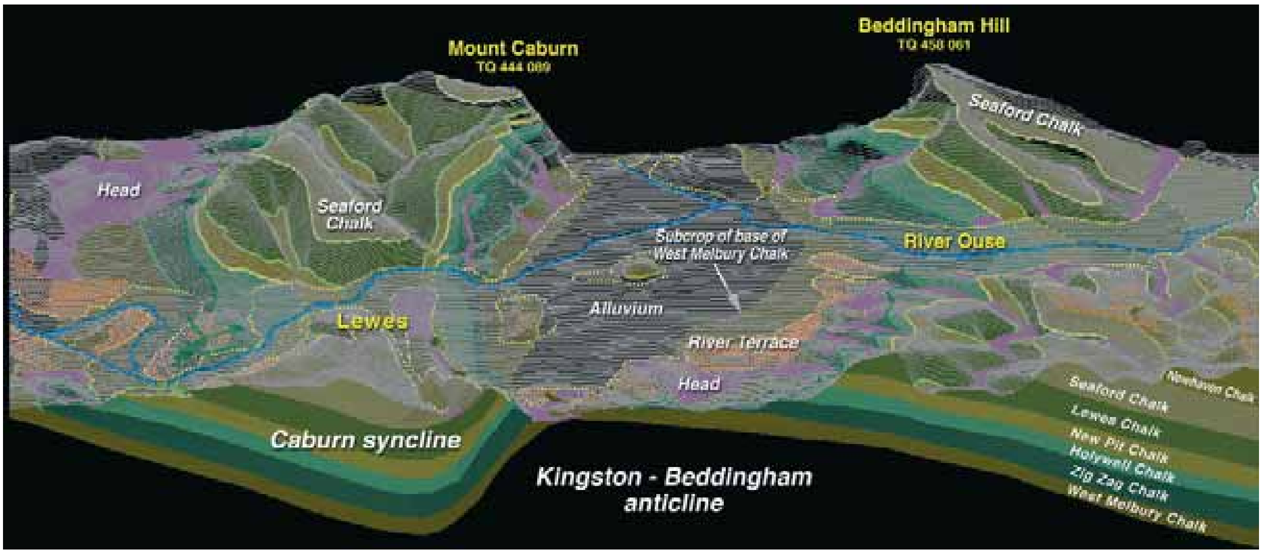


The models produced were:

- a 3D model of the top Chalk to land surface interval of the London Basin, based on early EarthVision™ files from the LOCUS project including
- several 3D models of the Chalk South Downs, Berkshire Downs, North Kent and the Frome–Piddle area catchment
- a 3D model of Mesozoic to recent surfaces in the Weald of south-east England
- a study of the applicability of property mapping of the Chalk using geophysical logs.

Several important points emerged from modelling in this area.

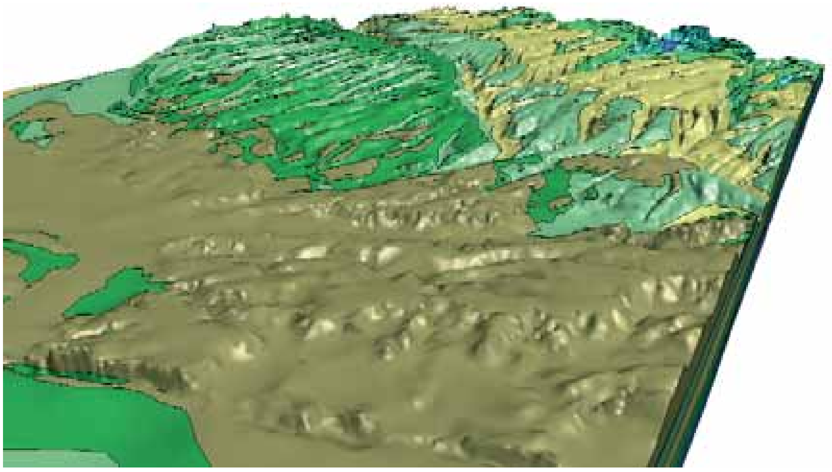
- Models produced for different areas varied in robustness, depending on the quality of the available data.
- The use of seismic in mapping the Chalk produced generalised structural maps, with some faulting evident. In many cases the Chalk was near the surface and its seismic response suffered from degradation due to uncertainties in near surface velocities and a lower degree of stacking, but depite this, many features not immediately evident at surface were discovered.
- The role of boreholes in mapping the Chalk was one of providing geological control for the seismic mapping and detail between seismic picks. However, the variable age and detail of the borehole records meant that there was, in places, a degree of uncertainty in the accuracy of surfaces.
- The building of the Weald model used borehole records that post-dated the original structural maps. The fact that modifications to the maps were to some degree systematic may imply that the basic mapping was more or less correct but that the process of depth conversion had introduced errors.



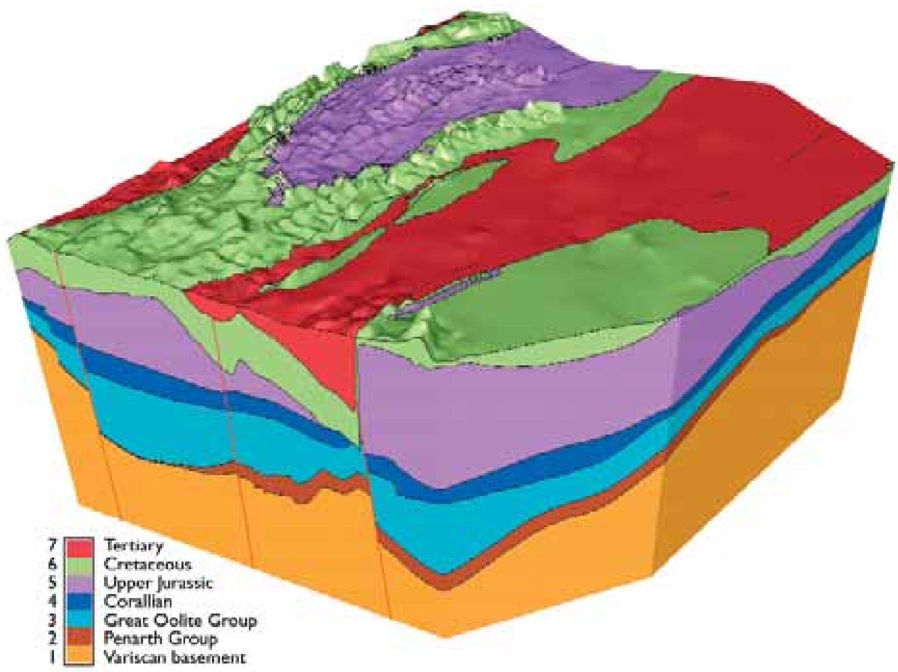
Oblique view east to illustrate geological structure in the Lewes area. Vulcan 'screen shot', vertical exaggeration x4.

A centre of population

South-east England



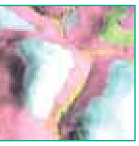
A 3D block model of east Kent (viewed from the south-west) displaying seven formations of the Chalk Group from the West Melbury Marly Chalk (dark blue) to the Seaford Chalk Formation (dark green) which are covered by superficial deposits known as Clay with Flints (brown).



A model of the Weald viewed from the south-west of the Isle of Wight, illustrating the inverted sedimentary basin and the major reversed fault controlling the Isle of Wight monocline.

Several important points emerged from modelling in this area. Models produced for different areas varied in robustness, depending on the quality of the available data. The use of seismic in mapping the Chalk produced generalised structural maps, with some faulting evident. In many cases the Chalk was near the surface and its seismic response suffered from degradation due to uncertainties in near surface velocities and a lower degree of stacking, but depite this, many features not immediately evident at surface were discovered.

Midland Valley of Scotland



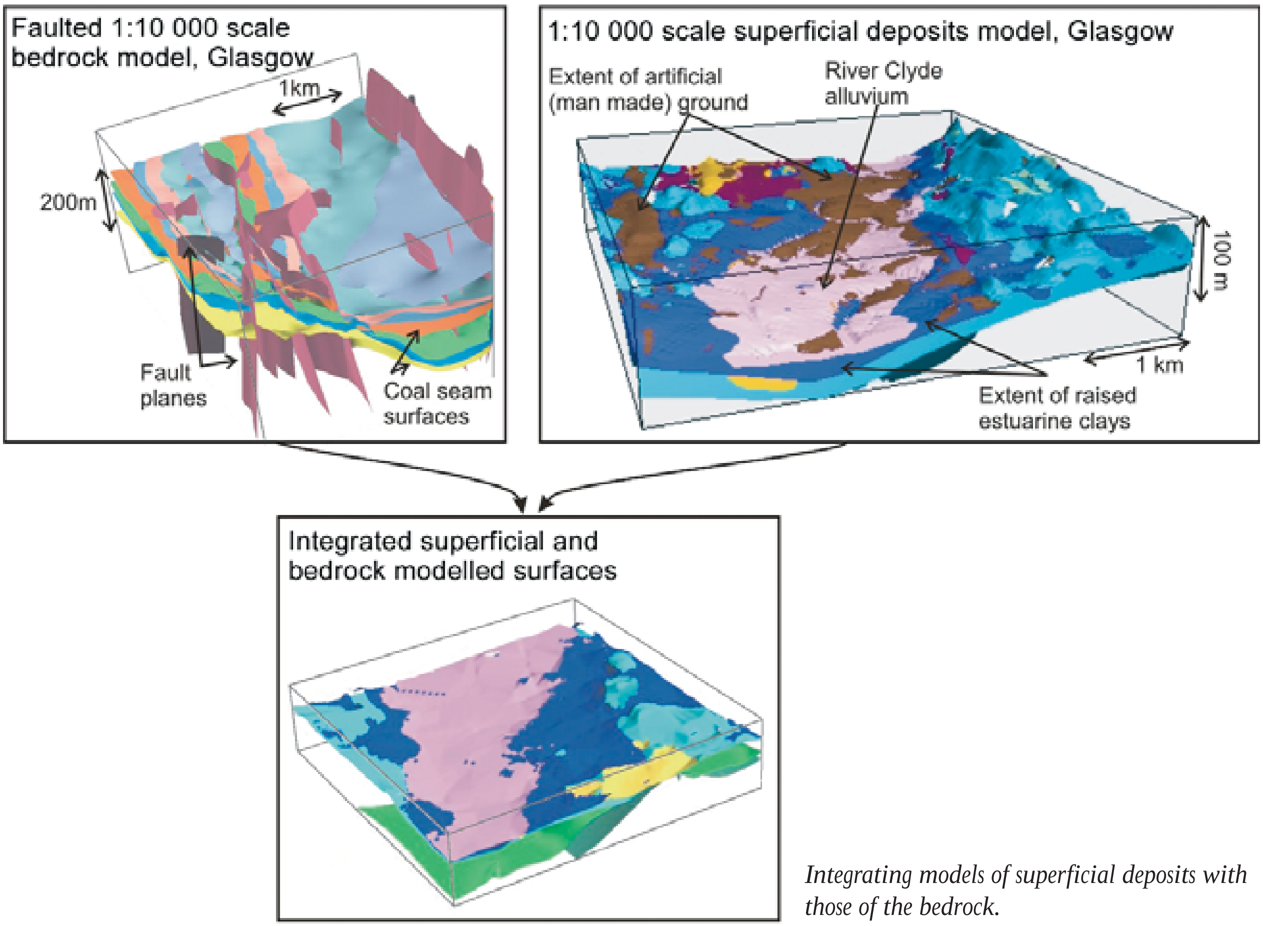
The Midland Valley of Scotland (MVS) terrane extends from the North Sea, through the central belt of Scotland and across to Northern Ireland. It contains faulted and folded Carboniferous basins with a complex structural history. Onshore, the structure of coal-bearing Carboniferous strata is constrained by a vast subsurface dataset of boreholes and mine plans — ideal for developing methodologies for modelling 3D faulted bedrock.

Offshore, and at deeper levels, seismic and geophysical datasets have been used to develop techniques for modelling geologically complex Palaeozoic–Mesozoic successions across the coastal boundary.

The project has been critical in developing the framework, especially for metadata, quality control systems, the storage of outputs and uncertainty studies. It has defined workflows for EarthVision™, Landmark™ and GoCAD™ software for bedrock modelling, and has integrated GSI3D superficial and bedrock models *(below)*. Over 25 DGSM best-practice or descriptive reports have been written on modelling techniques, export of model data, software interoperability, model merging, generalisation, integration of data at different scales, integrating geophysical data and interpreted points.

The longevity of the project and the number of models produced has facilitated studies of lateral and vertical model integration from scales of 1:10 000 to 1:250 000, and model generalisation from local to regional scales.

Techniques to integrate onshore and offshore datasets in an area of relatively continuous geology were developed in the Firth of Forth. The resulting model was later analysed using BasinMod™ and Hotpot™ to define the thermal



Integrating models of superficial deposits with those of the bedrock.

Midland Valley of Scotland

and burial history of a syncline-anticline pair *(below)* and a collaborative study with the University of Edinburgh explained oil generation pathways around this basin. By contrast, in the Firth of Clyde, procedures were developed to model markedly different onshore–offshore geology using datasets of varying scales and data distribution.

A pilot study with Midland Valley Exploration Ltd showed that the models could be structurally validated. Restoration of fault movements back through time increased our knowledge of basin tectonostratigraphical evolution.

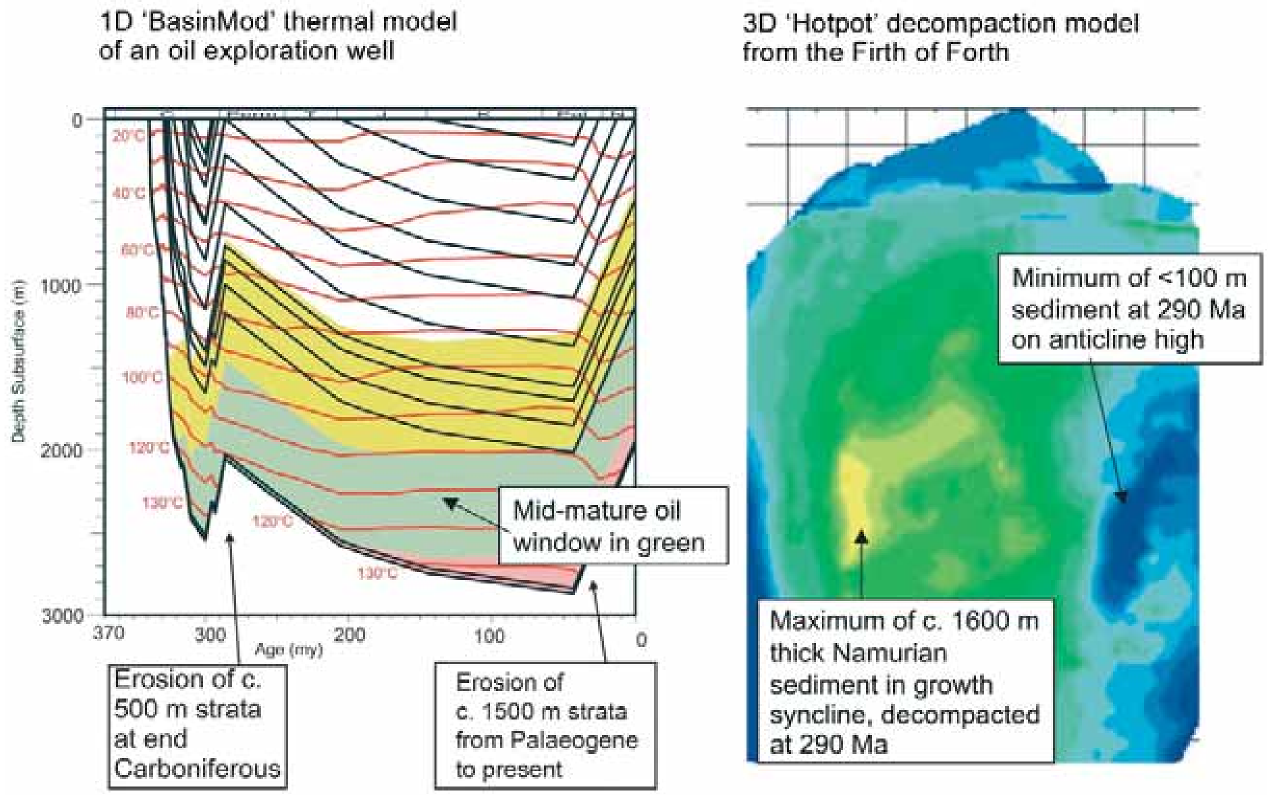
The work highlighted:

- the importance of overlap zones for model merging
- the need to understand and document the sizes and style of faults that should be be excluded when generalising models from local to regional scales
- the importance of interpreted points for capturing geologists' knowledge, and recording the rationale in the metadata

Integrating models at differing scales from data of differing quality requires that the modeller must make difficult decisions on the best data or model to use, based on geological knowledge and modelling technique. Metadata, quality control and assessment of uncertainty must be recorded *during* the modelling process.

The Midland Valley DGSM methodology is now embedded within major co-funded projects that will continue after 2005. Interest in the 3D subsurface information by users of BGS data, and the increased understanding of basin evolution have proven the value of the models and methodologies developed.

Burial and thermal history studies for basin evolution

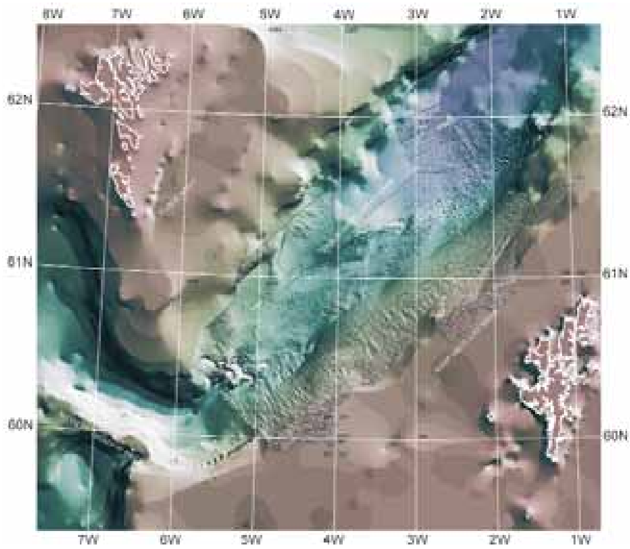


The Atlantic margin

The Atlantic margin area of interest is the offshore United Kingdom Designated Area (UKDA) to the north-west of the UK landmass. The BGS has a strategic responsibility to characterise the 3D geology of the offshore UKDA. The DGSM programme plays an important role in helping to achieve this aim.

The main objectives of this study were:

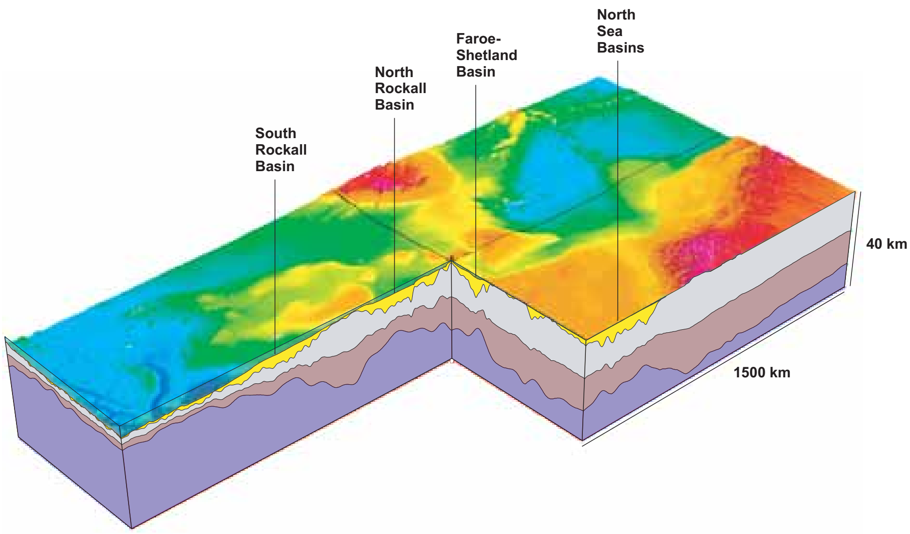
- to produce regional Atlantic margin geological models using a variety of data types, packages and platforms
- to document the modelling processes and procedures involved in the production of offshore DGSMs in the form of best-practice guidelines and checklists
- to test the DGSM framework. This involved testing many facets of the DGSM system that provide a modelling environment and allow, for example, the entry of model metadata and facilitate the display and storage of models within the GLOS and GSF.



Sea-bed image of the Faroe-Shetland area (after Long et al. 2004*).*

The main outcomes were:

- the compilation of a series of individual and merged offshore Atlantic margin DGSMs, most of which are mainly based on the seismic definition of surfaces. Models generated from previous BGS projects have been stored in DGSM-compatible form to ensure that they are properly preserved.
- the completion of numerous best-practice guideline and checklist reports pertinent to modelling activities and the production of offshore DGSMs.
- the provision of input and feedback regarding the development of the Digital Geoscience Spatial Model framework by Atlantic margin DGSM staff. In particular, significant effort was expended in the successful production of the model metadata capture system.
- the creation of a group of geoscientists experienced in modelling techniques and procedures developed by the DGSM programme.



Cut-away of a three-dimensional model of the north-east Atlantic margin, in which the structure has been optimised to provide the best fit with observed gravity anomalies. The top surface shows topographic variations. In the cross-sections:

yellow = sedimentary layer;

grey = upper crust;

brown = lower crust;

purple = upper mantle

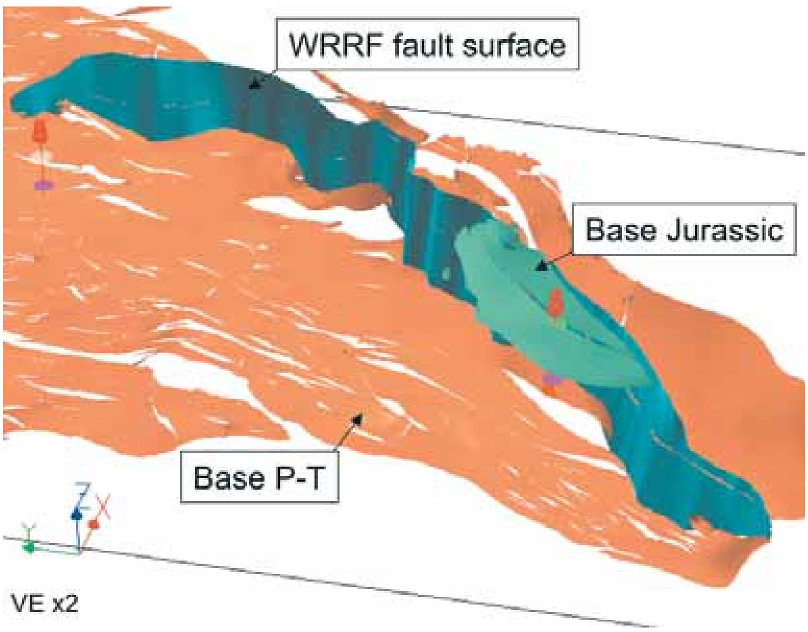
The Cheshire Basin

The Cheshire Basin was chosen as a DGSM population project as it was an up-to-date multidisciplinary project that encompassed a wide range of datasets, summarised in a major report[1]. The project included several different approaches to modelling and was, therefore, considered to be good test for the DGSM framework.

The basin structure had been modelled in 2D for the original project using EarthVision™. New 3D models were prepared in EarthVision™, GoCAD™ and Vulcan™, allowing the relative merits of the three packages to be compared. This process provided valuable lessons in migrating legacy data from 2 to 3D, highlighting the difficulty in incorporating complex faulting, which needs to be linked between individual layers for use in 3D. EarthVision™ modelling produces very attractive images of the models, but is less tolerant of inconsistencies and inaccuracies, compared to Vulcan™ and GoCAD™. The latter can handle large numbers of faults.

The project also investigated the incorporation of mineralisation, hydrogeological and basin evolution modelling into the DGSM. The evolution of the basin (burial depths, thermal history) was modelled using BasinMod™ software. Initially, 1D borehole models were produced, which were then linked to produce 2D models. In addition, the Cheshire Basin report was used for the development of text mark-up.

Structural models from EarthVision™ and GoCAD™ provided the starting point for groundwater flow modelling, using finite element analysis. This places severe constraints on geological modelling, because it needs simplified, tailored output requiring a lot of manual intervention. It proved difficult to get suitably simplified outputs for fluid flow and hydrochemical modelling from EarthVision™. GoCAD™ surfaces looked more promising, but were too detailed for use in a regional groundwater model.



Perspective view of part of the Cheshire Basin GoCAD model showing the faulted base of the Permo-Triassic basin and basal Jurassic outlier. The Wem-Bridgmere-Red Rock Fault (WRRF) forms the eastern margin of the half-graben basin.

Prospective areas for mineralisation were defined, based on the conceptual model of mineral formation developed for the original project and the improved spatial model. A wide range of datasets were used in Arc-Spatial Data Modeller (the ArcView add-in) to produce prospectivity maps. The prospectivity mapping defined data relationships at known occurrences of mineralisation. Each data layer was weighted against the known occurrences and integrated using weight of evidence to produce probabilities for mineralisation across the basin.

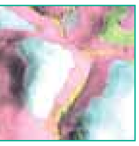
Outputs from all modelling were provided for loading into the GLOS and the lessons learnt fed into best-practice guidance and documented in more detailed reports.

[1] The Cheshire Basin: basin evolution, fluid movement and mineral resources in a Permo-Triassic rift setting. Edited by J A Plant, D G Jones and H W Haslam.

The British regional model

The regional model of Britain is designed to be suitable for presentation purposes, promoting the DGSM within BGS and to external parties. The resolution of the model is based on the 1:625 000 scale geological map of the United Kingdom.

The project has produced, for the first time, a 3D computer model of Britain's most significant subsurface layers, from the base of the superficial deposits down to the Moho, along with major faults and granites. A wide variety of sources have been used to construct the model, pulling together previously modelled surfaces, 2D maps and new modelling to create the final product.

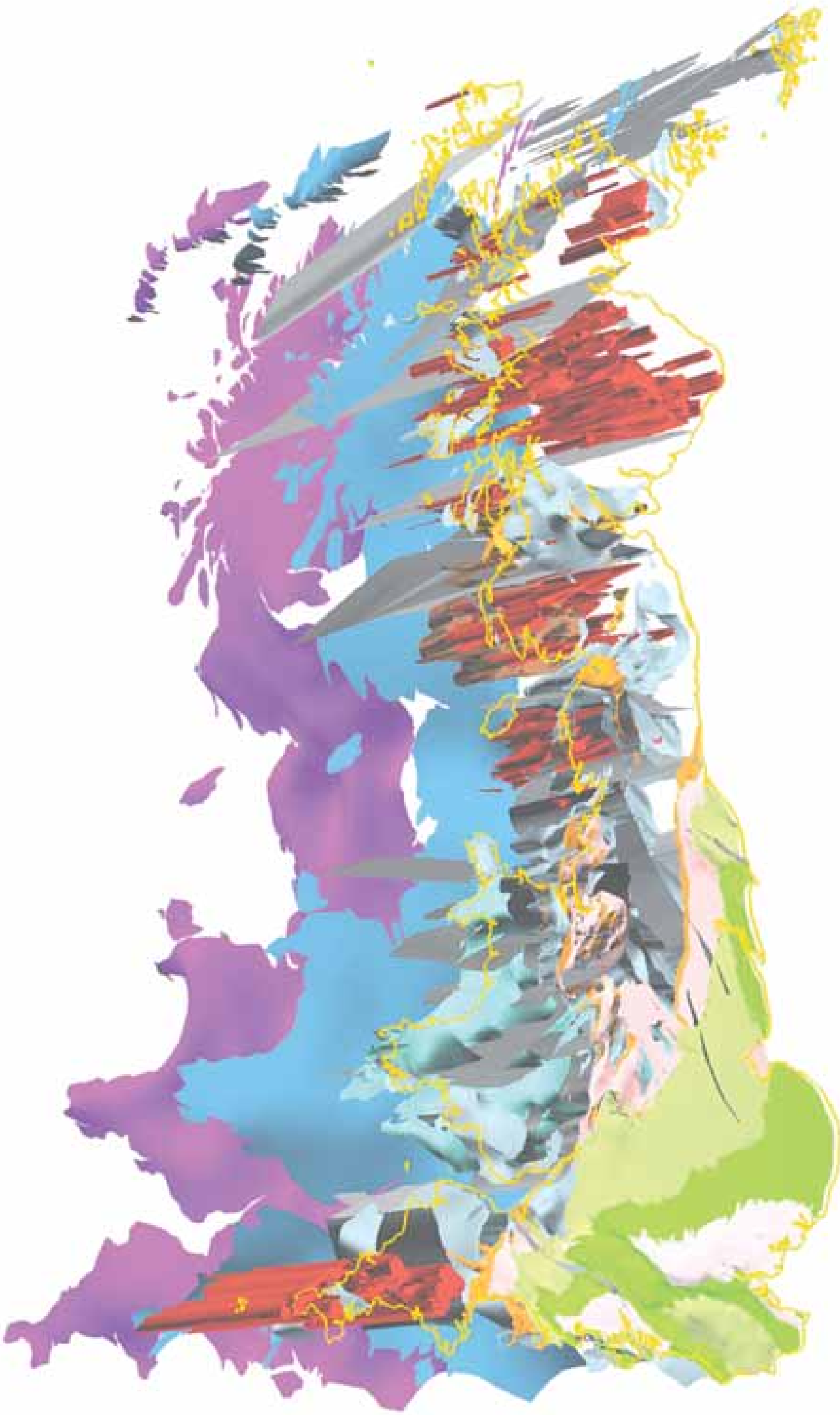


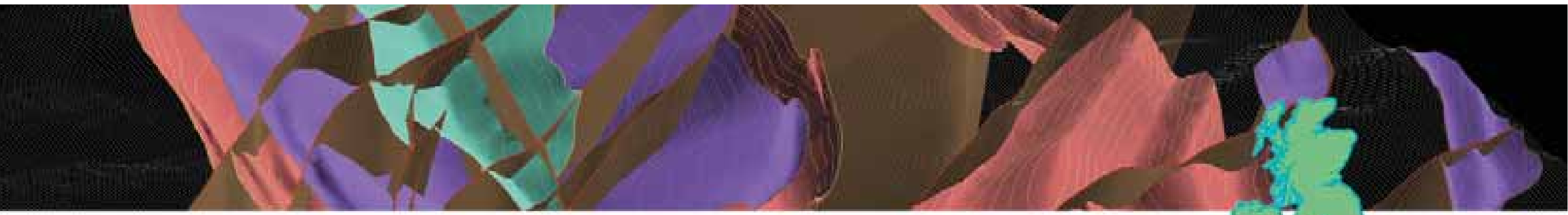
The model has a high visual impact and is of great interest to scientists, stakeholders and the general public as well as being the framework on which higher resolution models can be built. This model is consistent with the DGSM framework in terms of the creation of metadata, the storage of all the modelled surfaces in the GLOS and the GSF. Several demonstration movies have been created and are a fascinating insight to the geology of Britain in three dimensions. These will be made available for download from the DGSM website. Surfaces have initially been trimmed to the coastline of Great Britain, but in future will be extended offshore as data availability permits. Other themes have been added, including the foci of British earthquakes.

Surfaces included:

- land surface
- base of Palaeogene
- base of Cretaceous
- base of Jurassic
- base of Triassic
- base of Permian
- base of Carboniferous
- base Devonian (partial)
- base upper crust
- Moho
- major faults
- granites
- 1:625K geological map images (solid and drift)

The British regional model



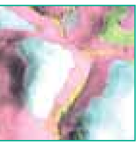


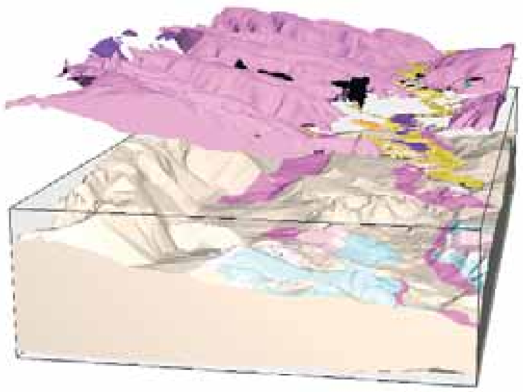
Nottingham–Melton

The purpose of the project was to produce a DGSM for the area covered by the Nottingham and Melton 1:50 000 scale geological map sheets. The models were based mainly on recent geological mapping, seismic reflection and borehole data. Different scales of models were produced but primarily it consists of a 3D lithostratigraphical model, developed from key surfaces at a resolution equivalent to a scale of 1:50 000.

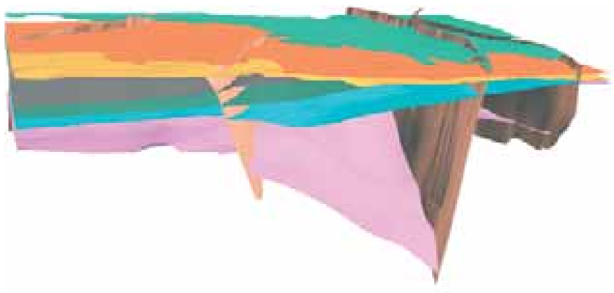
The project area crosses the Widmerpool Basin, which was an important sedimentary basin during Carboniferous times. A history of extensive coal mining and oil exploration in the area has left an important dataset which was used extensively for the project. Apart from defining a methodology for constructing a DGSM at this scale, it was also hoped that the model would result in a greater understanding of the sedimentary succession within the area, particularly the sedimentary and tectonic history of the Widmerpool Basin. The DGSM also has a potential role in

- the understanding of resource distribution and thickness (e.g. sand and gravel)
- subsurface risk assessment (including that from mining-related hazards)
- problems of rising groundwaters
- planning
- visualisation for public understanding of subsurface geology.





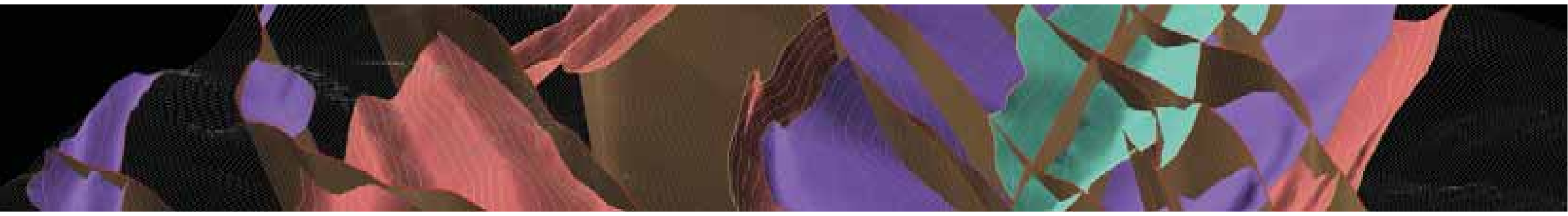
GSI-3D model of the River Wreake valley and surrounding area. This is an exploded view of the model, with the Oadby Till (pink) and younger lithologies displaced upwards by 150m. This allows the Bytham sands and gravels channel (magenta) and Thrussington Till (light blue) subcrops to be visualised.



GoCAD model to show the thickening of the Carboniferous succession into the Widmerpool Basin. The lowermost (pink) surface represents the top basement, the light blue surface forms the top of the Dinantian (Lower Carboniferous) and the turquoise surface is the Variscan unconformity. Although visually simple, this model results from an extensive and detailed evaluation of both seismic and borehole data in the area. There is a major fault on the right side of the model and clearly shows that the basin is a half-graben feature. In the basin centre the Dinantian is up to 3.5 km in thickness.

A number of models were produced by the project which provide improved visualisation on the deep and near surface (bedrock and superficial) geology of the area. A low resolution model of the entire study area is complimented by a series of higher resolution models of smaller areas. The low resolution model allows a clear appreciation of the deep structure and emphasises the amount of extension that occurred during Carboniferous times allowing a great thickness of sediment to accumulate within the Widmerpool Basin. Higher resolution models were able to incorporate the more detailed geological mapping work that has been carried out in the area recently. Building a series of smaller scale models showing increasing levels of geological complexity was thought to be a more suitable way of visualising the geology of the area, and overcomes any limitations imposed by software and hardware.

In the eastern part of the project area, the Carboniferous Saltby Volcanic Formation is present. This represents a succession of interbedded volcanic and sedimentary rocks. This was modelled using Vulcan™ software and a methodology was developed for complicated 3D lithologies. This work makes it easier to visualise the form of such highly variable successions. For example, it was

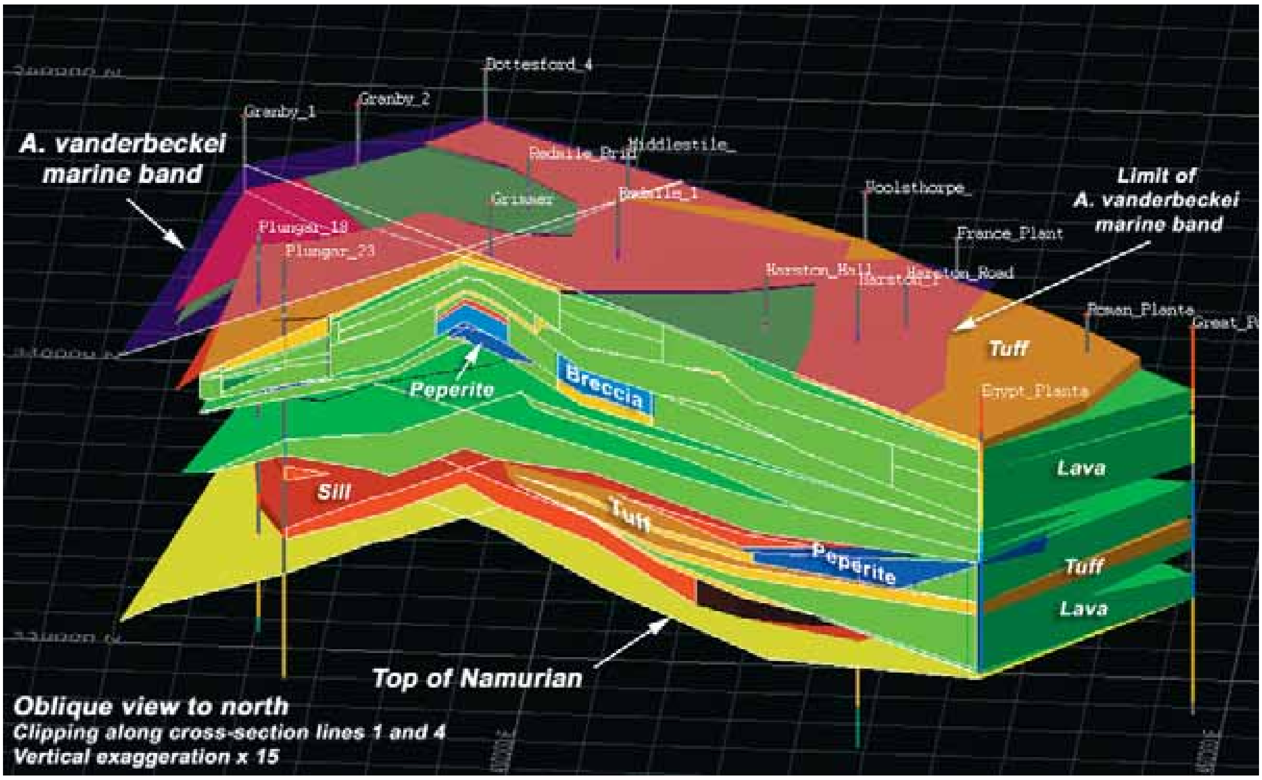


Nottingham–Melton

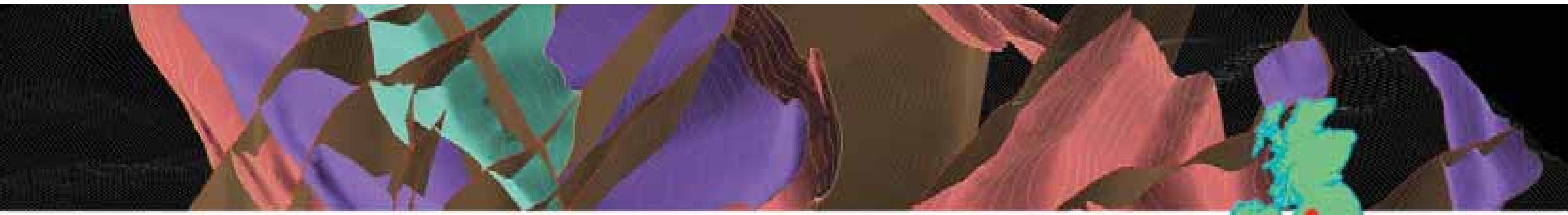
clear from the model that these volcanic rocks formed domes or topographic highs onto which later sedimentary successions, including the marine Vanderbeckei horizon, gradually transgressed/onlapped.

Since the inception of the project, the power of the GSI3D™ modelling application for working on the superficial deposits has become apparent. A GSI3D™ model of the Quaternary succession in the River Wreake area was produced showing the detailed distribution of the various ages of tills in the area and providing more information on a number of buried channels below the till.

The project brought about a better understanding of the work processes involved in model building, particularly the difficulties in moving data between software applications.



Vulcan model of the Saltby Formation. The Vanderbeckei Marine Band horizon (in purple) represents a major marine event of global significance at this time in the Carboniferous. However, in this area it can be demonstrated to thin and disappear onto the top of the volcanic succession indicating that this formed a topographic high. A low relief dome is envisaged, across which the marine event did not flood.

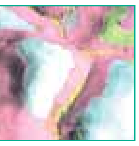


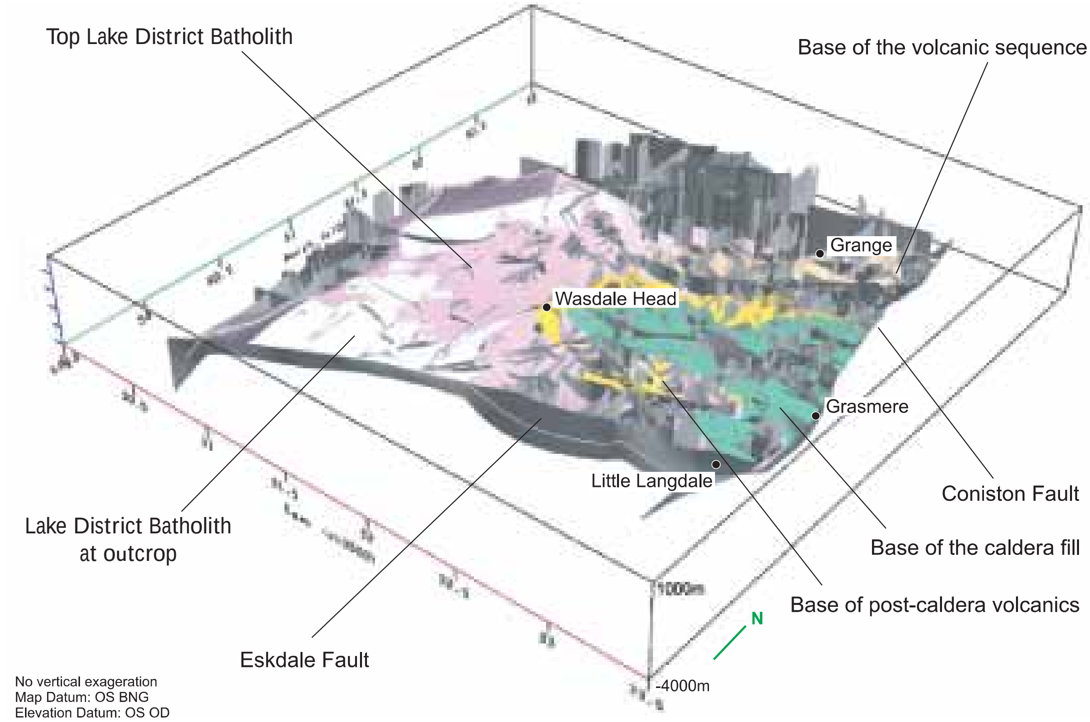
The Lake District

In areas of older rocks in the UK, where borehole and mining data are few, interpretations of the subsurface geology are extrapolated from surface observations and depicted as cross-sections and geological surface contour maps. This interpreted data provides a conceptual understanding of the geology, but the true depth, geometry and inter-relationships between subsurface horizons are often less well constrained. A methodology has been developed using interpreted subsurface data to build a well constrained and logically consistent 3D model of the English Lake District. Our example is from the complexly faulted Borrowdale Volcanic Group, the relic of 450 million-year-old caldera volcanoes.

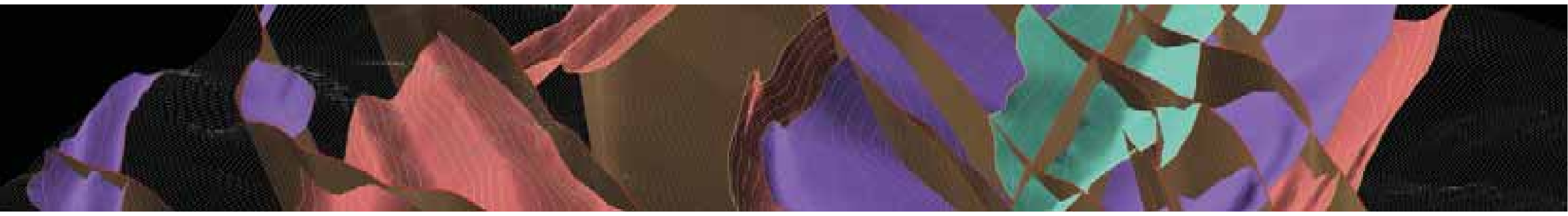
The geological model for the Scafell volcano has been built from interpreted datasets, including the framework of faults, geological map data, cross-sections and illustrative structure contour maps. Surfaces modelled are the base of the volcanic sequence, the base of the rocks filling the caldera, and the base of the overlying sequence of volcanic rocks. The top surface of the granite mass that underpins the volcanic sequence was constructed from published interpretations of gravity and magnetic data.

Confidence is critical to the modelling best practice developed. Rigorously objective assessments of positional uncertainty in each of the contributing datasets were used to derive a confidence plot that incorporates quantitative and qualitative aspects of geological uncertainty. The results were embedded in the model. Using this approach, the most appropriate spatial position of a subsurface horizon can be selected from differing datasets by comparing relative confidence scores. The resulting 3D model is a weighted best-fit solution and represents a significant improvement over a subjective average best-fit result.

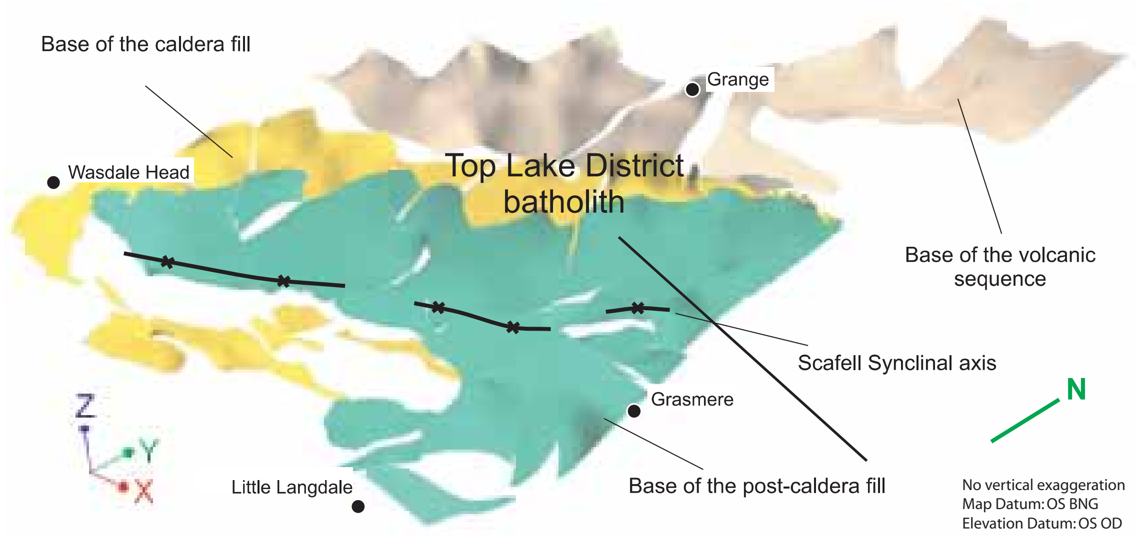




The final Borrowdale Volcanic Group model for the English Lake District. The image shows the full model including all elements of the structural framework.

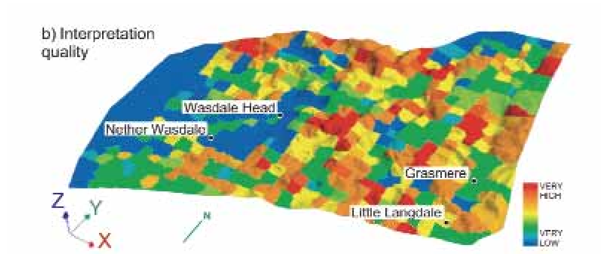


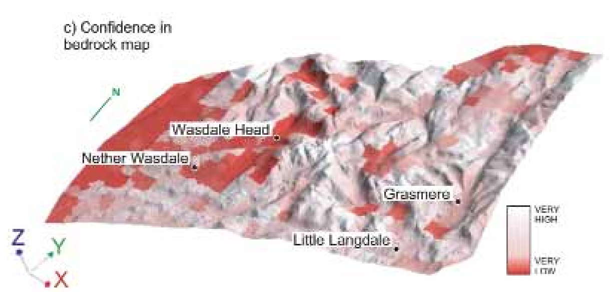
The Lake District

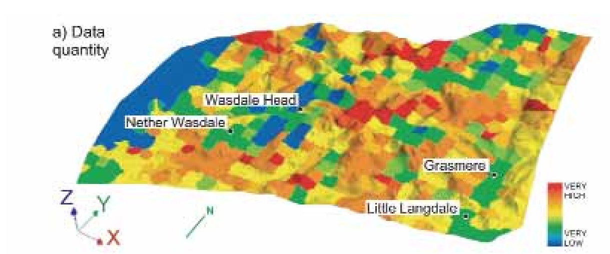


The Borrowdale Volcanic Group surfaces describe precisely the form of the broad fold structure, the Scafell Syncline, recognised in surface outcrop.

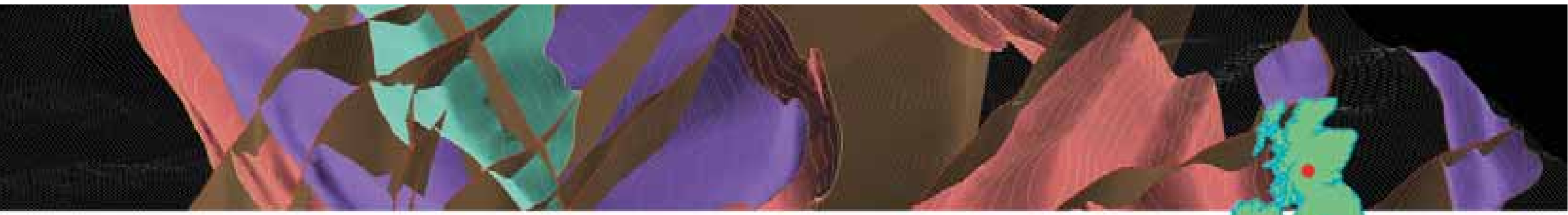
The geometry of the interpreted surfaces has been evaluated against primary structural data measured at the surface. There is a strong correlation between measured and modelled dip azimuths, but for the syncline formed by the base of the rock succession filling the caldera, the model predicts steeper limbs and a flatter hinge than is evident from the surface data. The weighted use of a wide range of interpreted data in the model construction results in high confidence levels for these parts of the model.







Examples of confidence assessment in the Lake District. The bedrock geological map has been assessed for both quantity of data (a) and quality of interpretation (b) on a square kilometre grid. Results are shown projected onto a 3D DTM. Assessments are combined to produce confidence values (c).

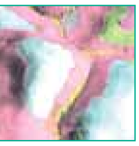


Glen Lochy–Glen Orchy

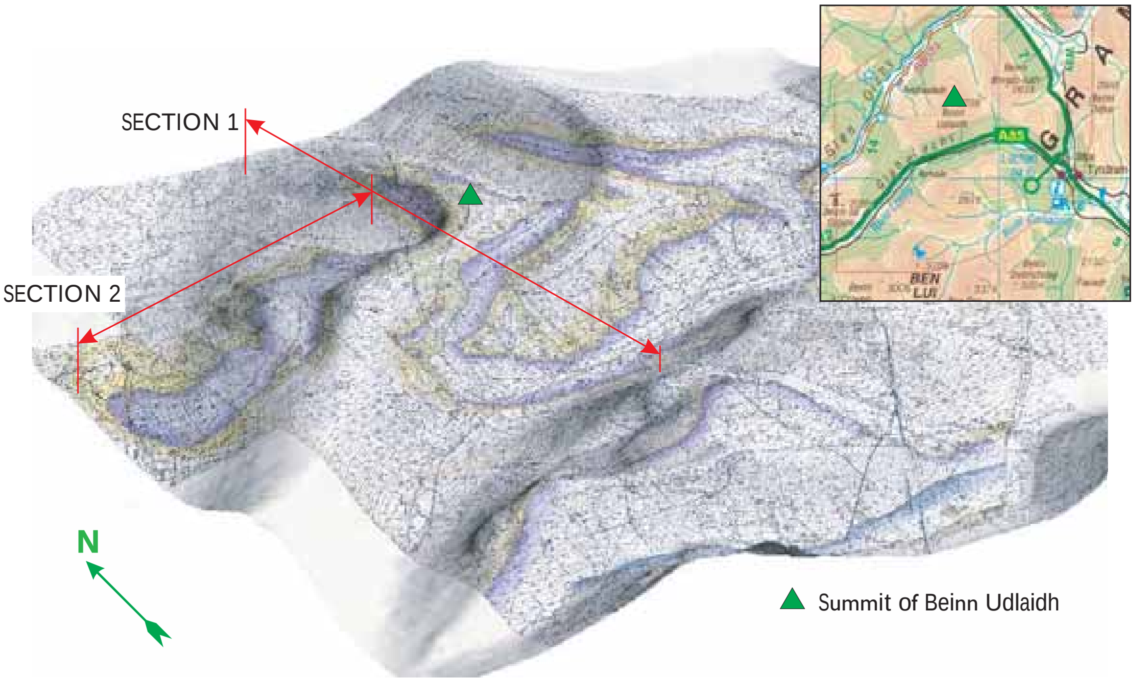
Complexly folded rocks severely challenge DGSM methodology. While a good conceptual interpretation of the structural geometry may exist, the concealed 3D geometry may have little or no underground constraint. For the modeller, overturned fold limb duplication in vertical sections undermines surface-building algorithms reliant upon unique depth intersections and thus requires special consideration in current practice. Recumbent kilometre-scale folds exposed on mountainous topography around Beinn Udliadh provide the basis for tightly constrained cross-sections linked in 3D. These constructions identify surfaces which potentially capture and constrain the georeferenced digital model, thus providing the geologist with significantly improved means of viewing, evaluating and interrogating the DGSM.

Compilation of new 1:10 000 scale mapping of Dalradian rocks in the Glen Orchy–Glen Lochy area is draped on the digital terrain model (DTM). The new geological maps, a fault framework, and cross-sections drawn through the critical parts of the structure are the primary inputs to a digital model. A full 3D surface representation is produced by treating upper and lower limbs of individual folds separately and then joining those surfaces at hinge lines identified from the cross-section constructions. Visualisations generated as still images, fly-throughs and animations make the model accessible to the user.

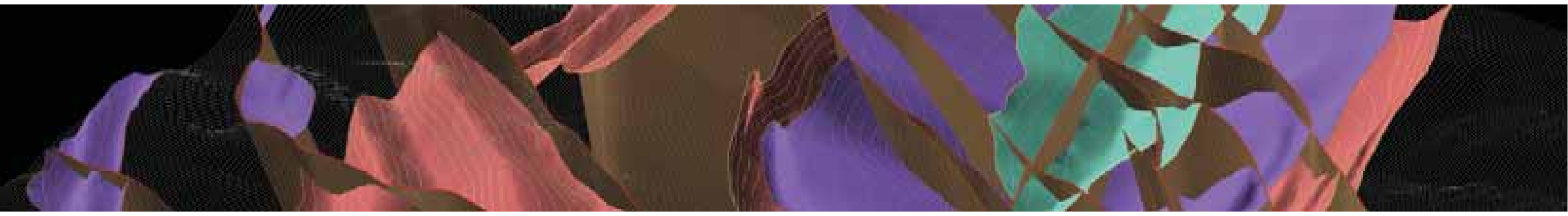
The DGSM is completely reliant on the geological field data to illustrate the structural geometry. A preliminary test for the model involved using it to decide whether or not surface exposures are compatible with the disputed existence of a 'Glen Lochy anticline' structurally below the Beinn Udliadh fold. The model has also been used to determine where the uppermost Beinn Chuirn anticline closes in unexposed ground to the south. On completion of the model, sets of structural contours have been drawn on modelled surfaces to demonstrate the geometry of the late domal structure constrained in the model. We still have to include the mapped igneous intrusions in the DGSM in order to establish whether or not there is any relationship between the domal structure, patterns of faulting, and the shapes and spatial arrangement of the igneous bodies.



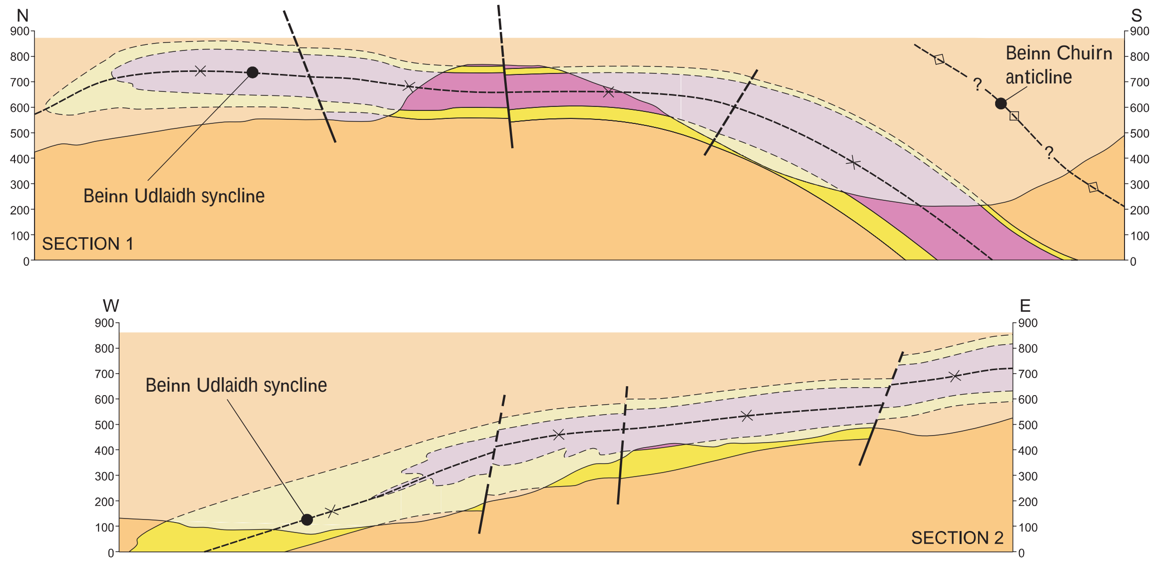
Modelling recumbent fold geometry



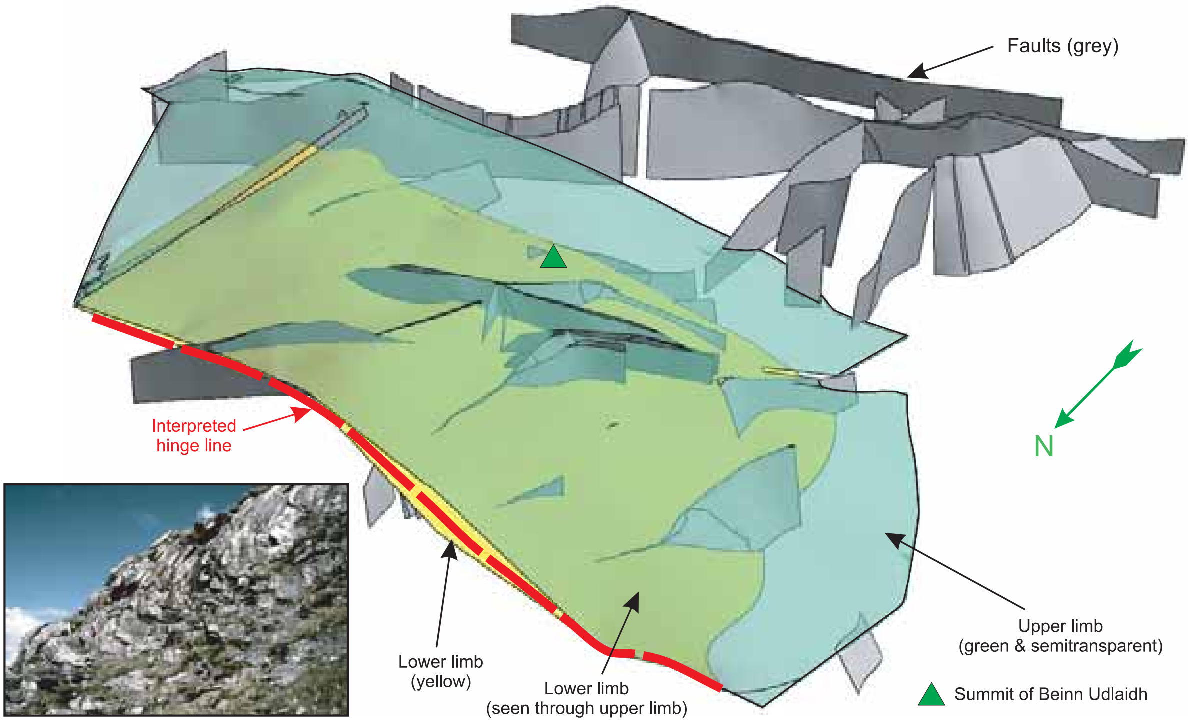
The DTM of the Glen Lochy DGSM area with the geological base map draped onto it. Insert shows the location in the south-west Grampian Highlands of Scotland.



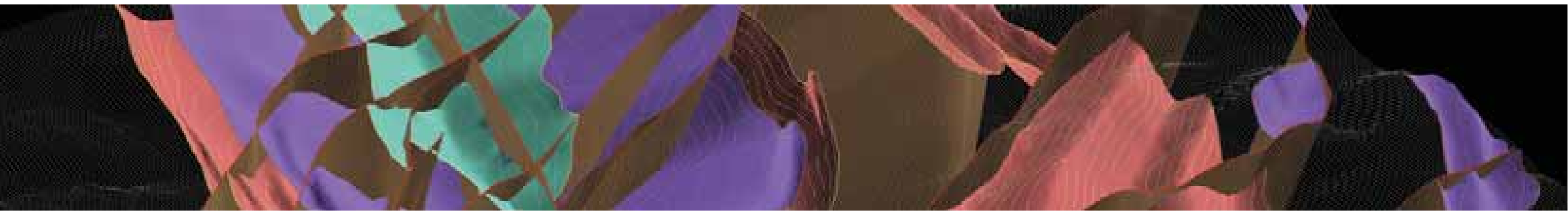
Glen Lochy–Glen Orchy



Representative cross-sections through the Beinn Udlaidh syncline.

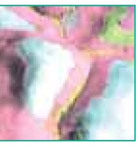


The Beinn Udlaidh fold structure (preliminary model) showing both limbs of the overturned fold, with photo of D2 folds in the hinge zone of the recumbent syncline.



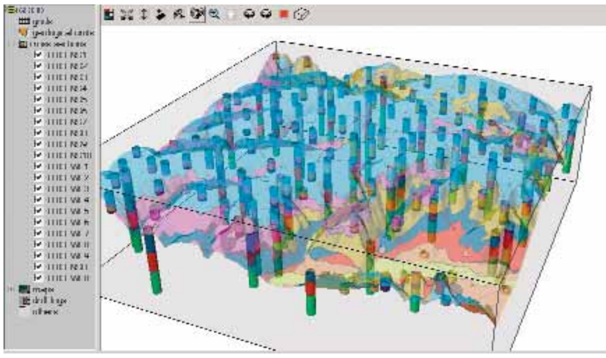
Aggregate resources

The BGS maintains a large legacy of borehole data from a contract carried out in the 1970s and 1980s, for the then Department of the Environment. This contract sponsored the Industrial Minerals Assessment Unit (IMAU), which investigated the complex and economically important layers of superficial geology containing sand and gravel resources.



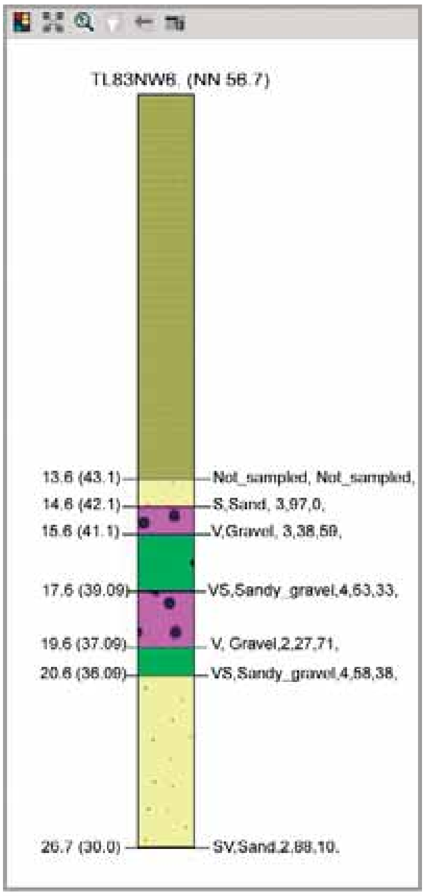
Using a small sample of the data, this DGSM project built high-definition 3D geological models of 400 sq km of terrain on the Suffolk–Essex borders centred on Sudbury. A complete set of 16 new digital 1:10K geological map tiles have been prepared for this area, incorporating significant revisions, based on the borehole coding, the IMAU resource grading data and the 3D modelling. In other words, the 3D models, the geological maps and the contributing data are fully consistent with each other.

The GSI3D software (originally developed by Dr H G Sobisch, INSIGHT GmbH, and extended in collaboration with the BGS acting as a test bed) was used to incorporate the slightly simplified IMAU grading data into the stratigraphical geological framework. This made it simple to visualise 3D models of the aggregate potential and to help define targets for detailed resource assessment and extraction. The output has been discussed with key organisations within the aggregate industry and the work has been presented at several major national conferences to gauge interest and possible involvement of this sector in the further development of the technique. The methodologies and tools developed are applicable to the treatment of the vast quantity of legacy data which exists over large parts of the UK and in particular south-east England.



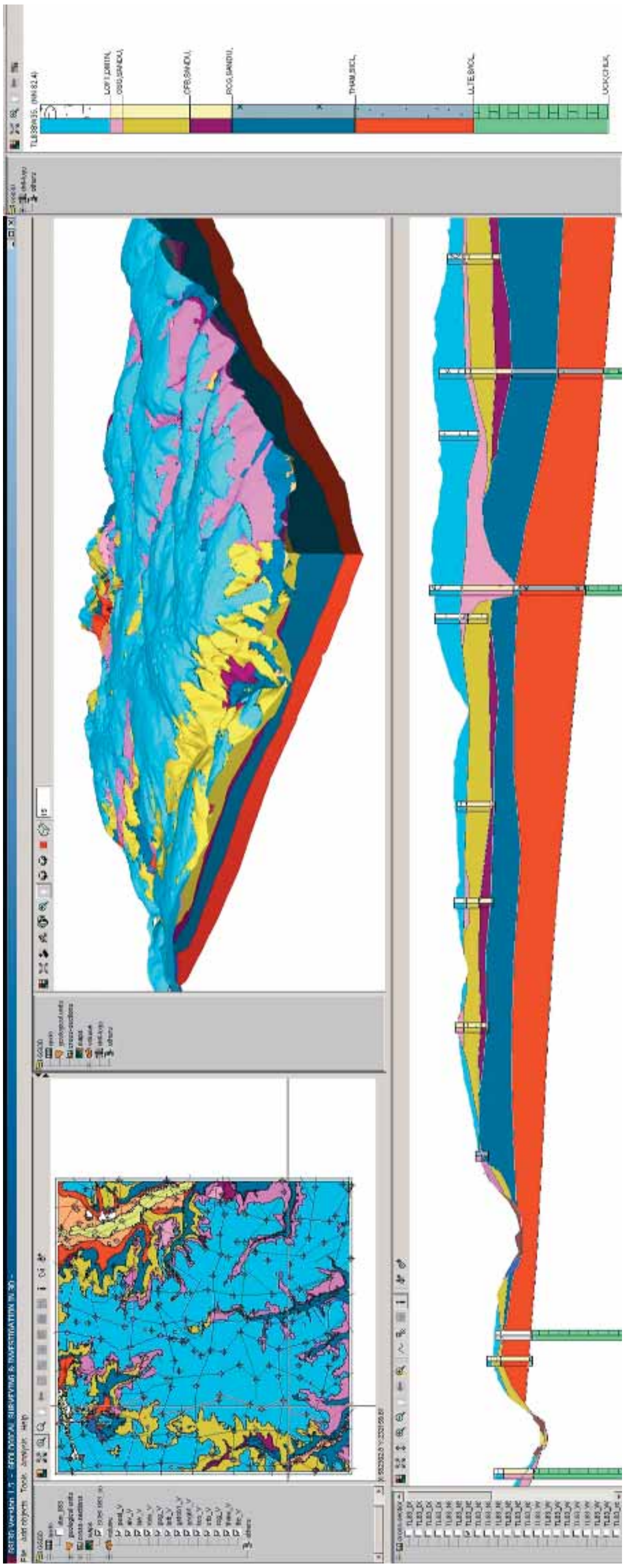
Stratigraphically coded borehole sticks for TL83 with the combined superficial and bedrock geology as a transparent drape on the DTM.

The project prepared dictionaries and methods so that all the data gathered during the IMAU surveys can be migrated into the corporate borehole geology and property databases, together with methods of displaying individual grading data within the GSI3D modelling environment. All the data outputs from the modelling are available in XML format and are lodged in the corporate GLOS and GSF datastores. Best practice has been documented and metadata compiled comforming with BGS corporate standards. The experience gained has been used to propose the criteria for developing LithoFrames 10 and 50 for south-east England. All of these elements will enable subsequent systematic modelling for the region to proceed.

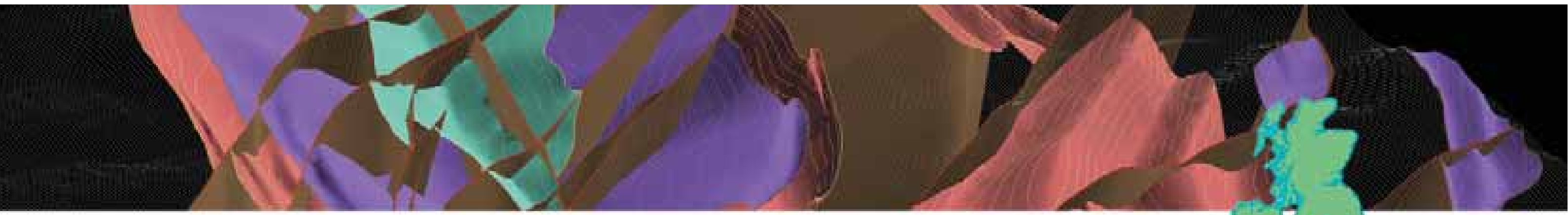


(left) *Specimen borehole log colour coded on the basis of grain size using a slightly simplified system derived from the IMAU sand and gravel triangular classification diagram.*

Aggregate resources



Geological modelling of the TL83 1:25 000 sheet within the GSI3D environment, showing (clockwise) the map, 3D, borehole and section windows.

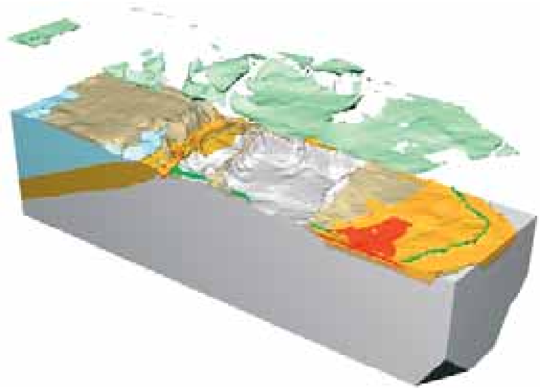


Thames Gateway

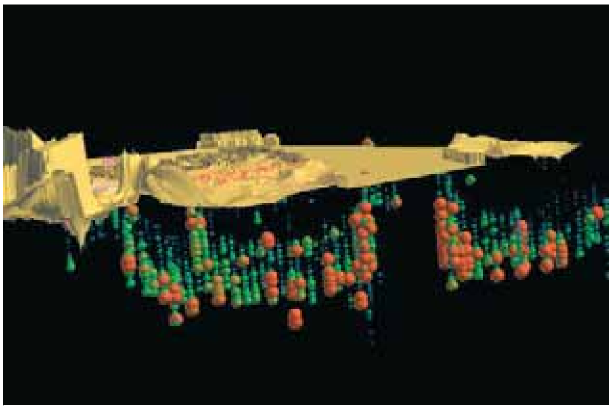
The Thames Gateway is the biggest building programme the UK has seen for over 50 years. It covers a 40-mile stretch of land along the Thames, from east London out into Essex and Kent. The key areas for redevelopment have been identified. So if this has already been decided, why do we need to understand the geology?

The Thames Gateway has extensive areas of difficult ground, including soft soils, high groundwater levels, and contaminated sites. Cost-effective forward planning decisions can only be made when the potential impact of such factors is considered. If sound decisions are to be made, then clearly those organisations involved in planning and development need easy access to all relevant information.

Rapid developments in 3D modelling software are now providing challenging and exciting possibilities for constructing high-resolution geological models of the shallow subsurface. Using this new technology (supported by our geological and geotechnical archives), we can predict not only the type of rocks that lie beneath our feet, but also their engineering properties (rock strength, shrink-swell characteristics and compressibility) and hydrological properties (permeability, porosity, thickness of the unsaturated zone or the presence of perched water tables). The data can then be imported into standard GIS packages and queried along with other complementary GI



Foundation condition block model for West Thurrock shows how new modelling techniques can not only tell you about the type of rocks beneath your feet, but also their physical properites.



Distribution of standard penetration test (SPT) values in the Dartford Crossing area, red = high, green = intermediate and blue = low.

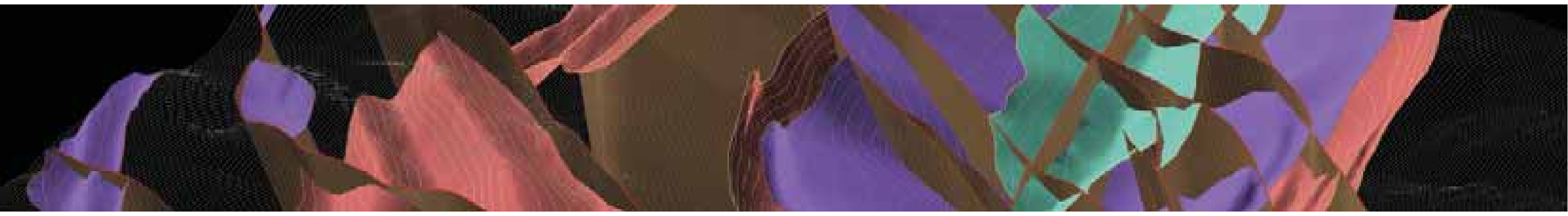
data, resulting in a powerful tool to assist in strategic planning and sustainable development. The 3D geological map can be queried, sliced, diced and uncovered to answer any specific questions asked by users who need to understand the make-up of the ground beneath their feet.

Sustainable urban drainage and urban flooding

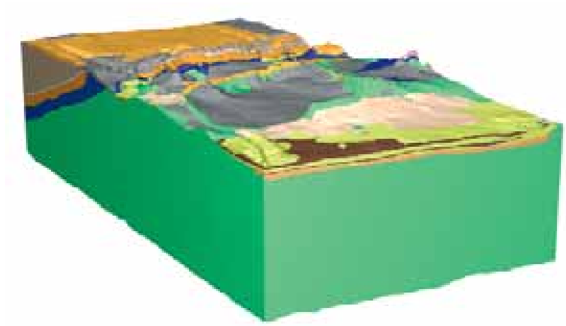
With escalating development and the growth in urban areas of hard paved surfaces, the problems associated with surface water runoff are a significant issue. The Foresight project (2004) predicted that the continued urbanisation of flood-prone areas, such as the Thames Gateway, could result in an increase in surface water runoff, with an increase in flood risk of up to three times its current level.

SUDS (Sustainable Urban Drainage Systems) are an alternative approach to conventional drainage systems that try to mimic natural drainage patterns as far as possible. The successful implementation of SUDS techniques, including swales, balancing ponds and porous pavements can save money, reduce pollution and alleviate flood risk.

SUDS techniques need to be addressed at the early stages of project design to determine their suitability. The BGS has developed methods that allow the applicability of SUDS to be assessed quickly and simply, by reference to the 3D lithological model (rock type e.g. sand, clay, peat etc). Data used in the assessment includes: the topographic slope angle; the permeability of the near-surface deposits; and the thickness of the unsaturated zone. The BGS can



Thames Gateway



A 3D block model of Thurrock displaying in detail the geology of the area. In this case, peat deposits (brown) are revealed beneath clay (yellow) sequences and overlying gravel (orange) and man-made (grey) deposits. Chalk bedrock is in green.

then provide charts that combine all this information into a simple tri-category map; areas more suited to infiltration techniques can then be easily identified. Further information can be added such as the potential for contamination, present day land use and aquifer vulnerability. All this data can be easily incorporated into the model resulting in a more sophisticated site-specific interpretation. These maps provide answers at a click of a button and can be viewed in most GIS software packages.

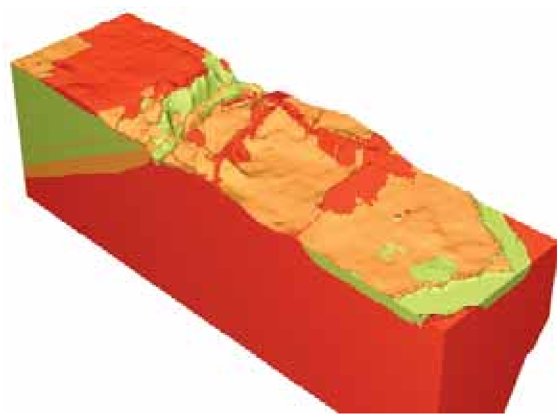
Subsurface (foundation) conditions revealed in 3D

Three-dimensional models of foundation conditions are derived by linking the lithological model with geotechnical (physical and mechanical) properties such as soil moisture content, strength, and consolidation characteristics. The BGS has created such a model for West Thurrock.

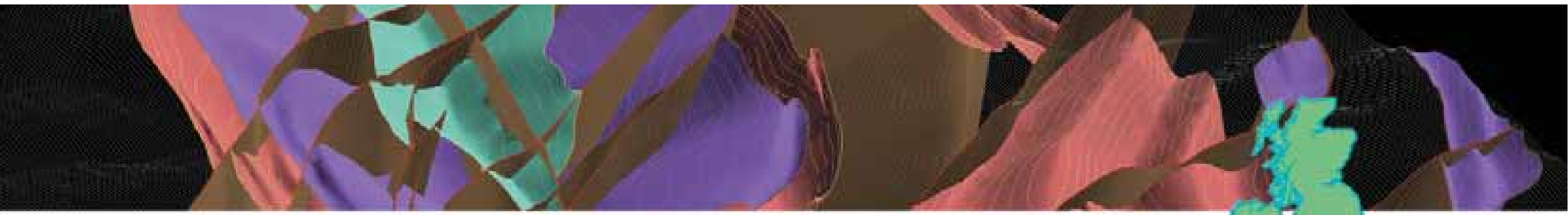
In West Thurrock the ground conditions were split into nine different categories. These varied from very compressible, corresponding to the presence of peat, to areas classified as only slightly compressible, which included the river terrace deposits and engineered made ground. Chalk underlies the whole area and is considered to be variably compressible. The reason for this is that at rockhead (the surface between bedrock and overlying unconsolidated material) chalk may have weathered to 'putty' chalk, which has similar characteristics to silt. This results in chalk close to rockhead often having an irregular karstic surface characterised by sinkholes. In general, foundation conditions within the chalk improve with depth from rockhead. But, how deep do we have to go before we can be certain of reaching unweathered chalk? The 3D foundation model can answer this question, by using the geotechnical data to derive a zone of weathered chalk below which the chances of encountering sinkholes is much diminished.

The 3D model of foundation conditions gives the user the ability to evaluate the ground conditions at the level that building is to take place. In the West Thurrock area, ground conditions viewed at 2 m below surface are different to those observed on the surface. At 2 m nearly half the area's ground conditions are classified within the highly to very compressible category. At 5 m below surface, this situation has changed again; now only a very small proportion of the area is marked as highly compressible. This type of data can be used in a myriad of ways from predicting how difficult in engineering terms a project is going to be, to selecting preferred areas for development.

The BGS is striving towards producing 3D geological 'property' models, which may be readily accessed, viewed and queried by a wide range of users as their needs arise. These models are also allowing scientists to begin to understand the urban earth system and how development effects our environment.



Hydraulic conductivity block model of the Thurrock area, red = high, orange = intermediate and green = low.



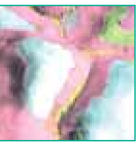
Humber Estuary

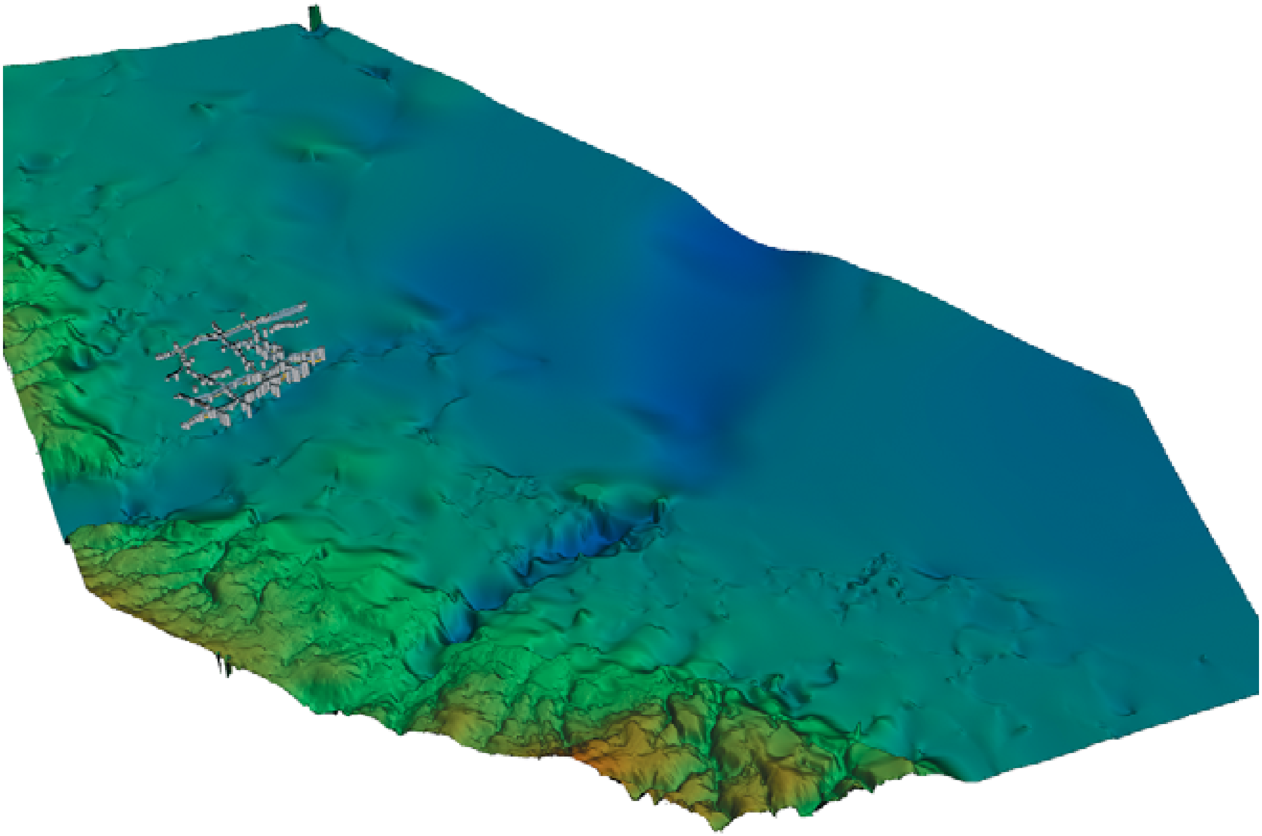
The Humber Estuary DGSM project was designed to collate and refine models of the Quaternary and Holocene succession of this active estuary. The main aim was to evaluate methods for modelling coastal and glacial deposits and assess their role in interacting with shallow aquifers. It enables users to visualise geological interpretations of the estuary and surrounding Quaternary succession. It includes the best understanding available at the time and explores information associated with the interpretation to extract key spatial and property data. In particular the project aimed to:

- migrate LOIS (Land Ocean Interaction Study) data to corporate databases
- model the base of Pleistocene and Holocene deposits in the Humberside area
- build a detailed model of the Quaternary strata underlying the city of Hull
- develop a groundwater flow model of the area using finite element meshes
- mark up two geological memoirs to enable easy access to text
- carry out confidence testing of the geological models
- document experiences in best-practice documents.

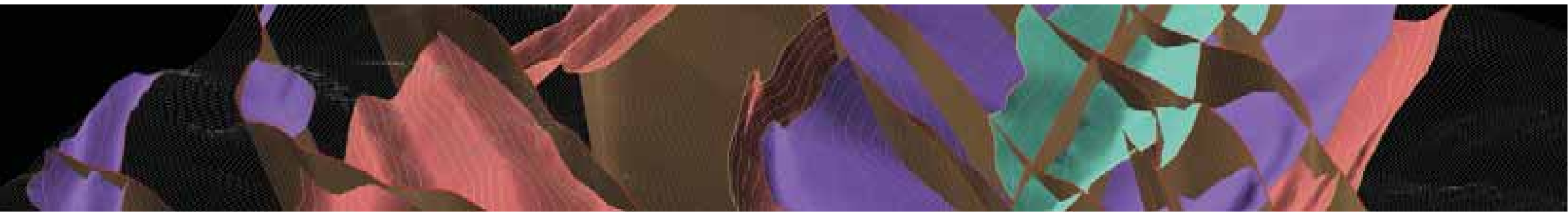
As a result:

- all LOIS boreholes are now available in the corporate borehole database
- six modelling packages were tested on TA11 and the preferred one was chosen to develop a rockhead model for the Humberside region
- the bases of the Holocene and Pleistocene for the Humberside area have been deposited in the corporate data store

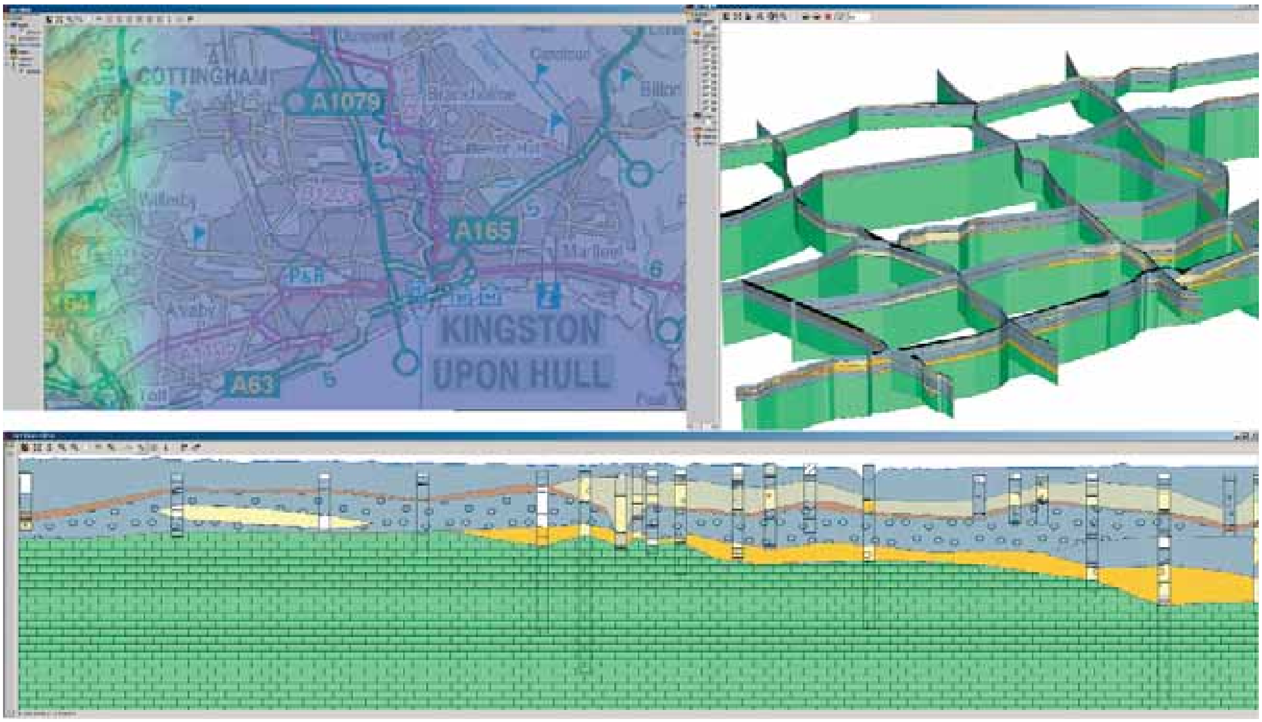




The Humber rockhead model and the Hull detailed correlations viewed from the south.



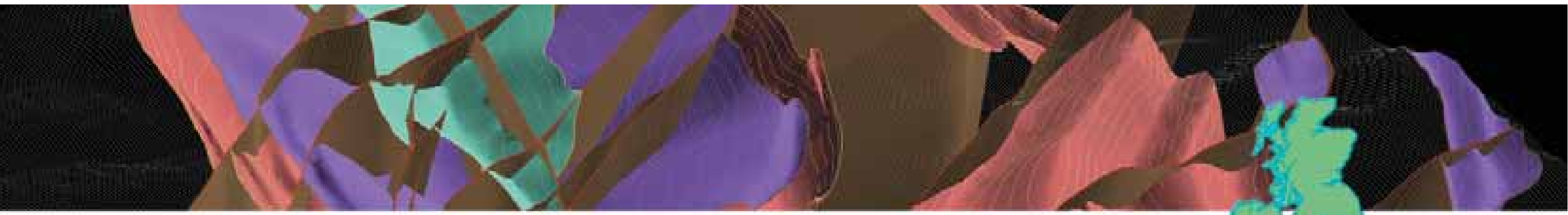
Humber Estuary



The Hull detailed quaternary model showing Holocene and Pleistocene deposits overlying the Chalk aquifer in green.

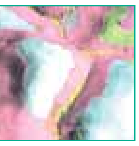
- a detailed Quaternary model has been constructed for Hull city
- two memoirs (Patrington and Hull) have been marked up
- a finite element mesh for TA11 was developed in GoCAD.™

What we have found that it is vital that future onshore/offshore modelling projects populate the same corporate databases to agreed standards. The quality of borehole coding, downhole lithologies and index data, was crucial for the quality of the resulting 3D model. In low relief coastal areas the quality of DTMs is often unsatisfactory for modelling and borehole start heights should be used with caution. All six modelling packages tested were able to create a satisfactory surface from scattered borehole points. MapInfo Vertical Mapper was chosen for the rockhead modelling due to the ease of data manipulation and user friendliness. GSI3D™ is very well suited to the modelling and visualisation of high detail, complex Quaternary sequences. The extreme aspect ratio of shallow Quaternary models requires great care in the use of GoCAD™ during the generation of the mesh and in the numerical solution of the finite element equations.

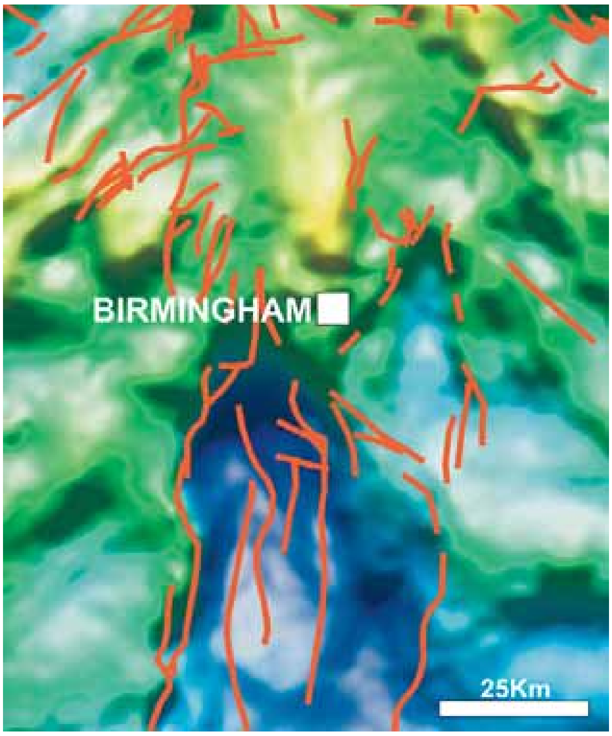


West Midlands

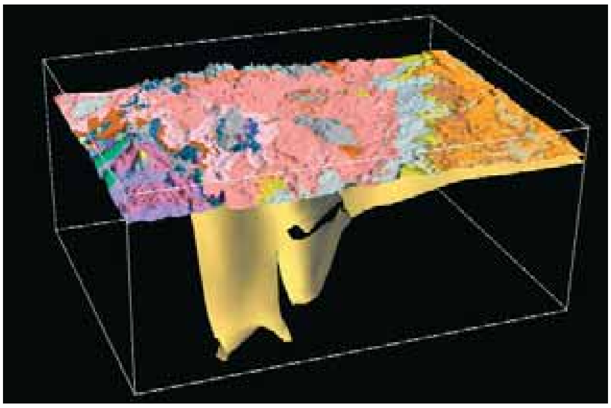
The DGSM project and the BGS Wallingford National Groundwater Survey (NGS) have co-funded 3D modelling studies on the Permo-Triassic sandstone aquifers of the English Midlands. An understanding of geology in three dimensions is critical to many groundwater issues such as resource management and potential contamination paths. The English Midlands is a complex geological area with deep fault-bounded basins and intervening highs. The basins were infilled with thick Permo-Triassic sandstone sequences which form important aquifers for Birmingham and the surrounding area. The primary objective was to use DGSM protocols to model four surfaces within the Sherwood Sandstone aquifer. Data sources included boreholes, seismic sections and a compilation of pre-existing contour maps gathered from maps and memoirs.



The resulting 3D models have provided an insight into the deep geology of the area and have also allowed the generation of new contour maps, showing for example, thickness of aquifer/aquitard and depth to aquifer, which will be published in the NGS memoir. The reduction of 3D models to 2D maps as a final product may at first appear a retrograde step, however, 3D visualisation provides a powerful means of testing the validity, and refining the contours of a 2D map.

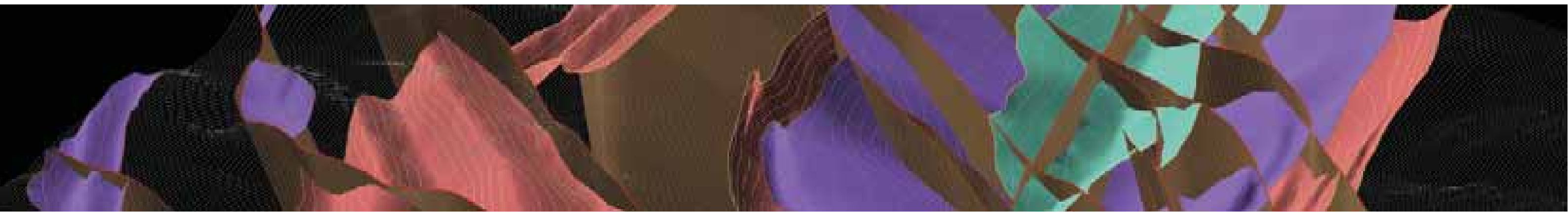


Map showing the area of interest. The shaded gravity anomaly map shows the complex array of basins (cool colours) and hights (warm colours). Major faults are shown in red.

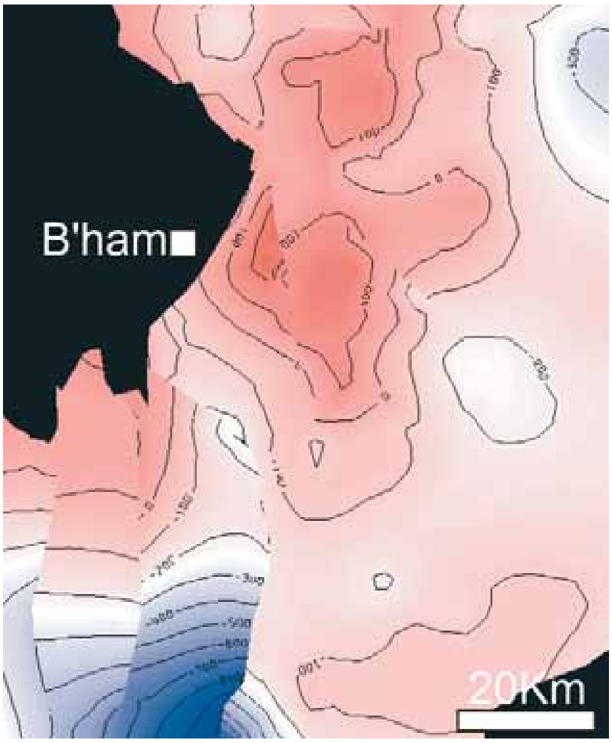


Solid geology of the English Midlands draped on a DTM with the basal faulted surface of the Permo-Triassic succession.

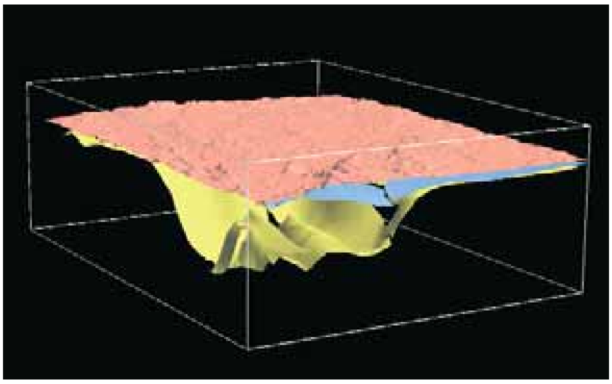
In addition to modelling lithostratigraphical and fault surfaces, GoCAD has been used to model regional variations in the elevation of the water table. GoCAD provides a powerful tool to explore the relationship between groundwater level and topography, stratigraphy and structure. Abrupt steps in groundwater level have been shown along several faults which show that they are acting as permeability barriers.



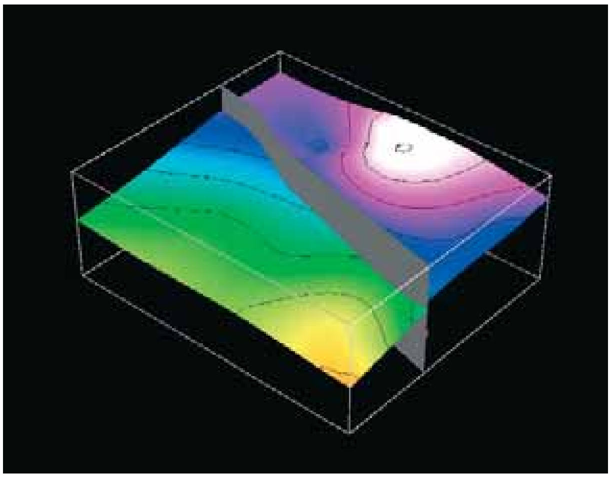
West Midlands



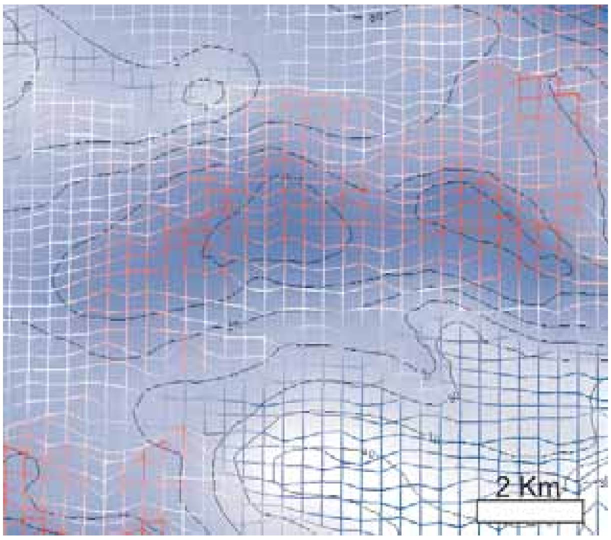
Contour map of the base of the Bromsgrove Sandstone.



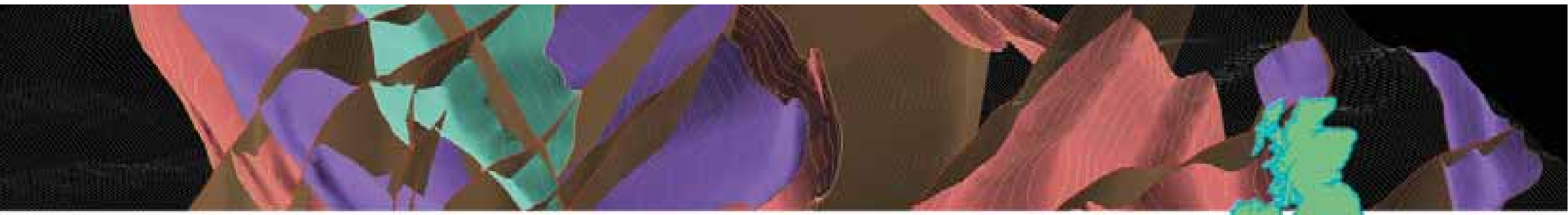
The base of the Mercia Mudstone Group (blue surface) broadly divides the basin fill into synrift and postrift sequences. The base Permo-Triassic surface is shown in yellow and land surface in orange.



The relationship between abrupt changes in the elevation of a groundwater surface and the position of a fault plane (here acting as a permeability barrier).

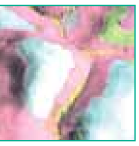


The relationship between groundwater level (blue surface) and topography (mesh).



The Welsh model

The Lower Palaeozoic rocks of mid-Wales are heavily faulted and folded, as well as having a complex sequence of interdigitating basinal rocks including turbidites, shales and volcanic successions. In order to understand the process of modelling where there are almost no subsurface data such as boreholes or geophysical survey results, it was decided to build a model of a small part of the BGS 1:50 000 scale Rhayader Geological Sheet (179), which is representative of the region.



This area consists of a sequence of turbidites of Llandovery (Silurian) age which have been strongly folded into a series of *en echélon*, generally north-north-east trending open, asymmetrical periclines. There are numerous subsidiary folds, and dips range between 25° to locally vertical or steeply inverted. It is cut by a system of steeply dipping faults which postdate the main folding. Most of the faults have an east-north-east trend, downthrown to the north-west. The area is covered by superficial deposits, consisting of thin peats on the upland interfluves, and extensive till and alluvium in excess of 20 m thick in the valleys.

The model was created in Vulcan, which is particularly suited to modelling complex structures. The only controls on the interpretation were the outcrop/subcrop positions at rockhead, scattered dip/strike measurement locations at the surface and the published cross-section.

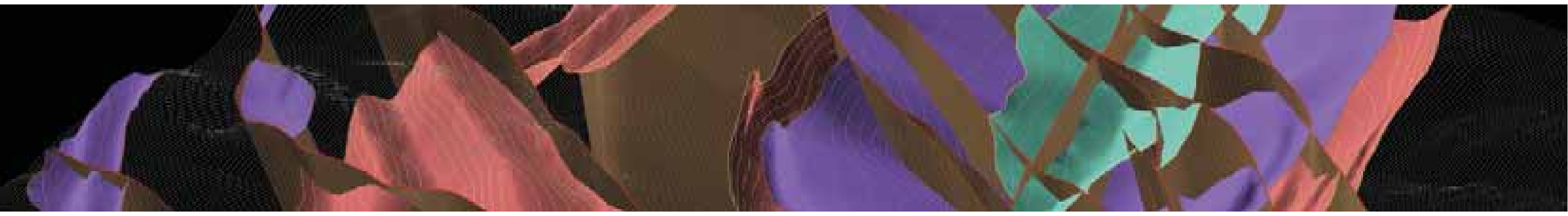
The following major stratigraphical surfaces were modelled:

- base of the Glanyrafon (Upper) Formation
- base of the Pysgotwr Grits Formation
- base of the Glanyrafon (Lower) Formation

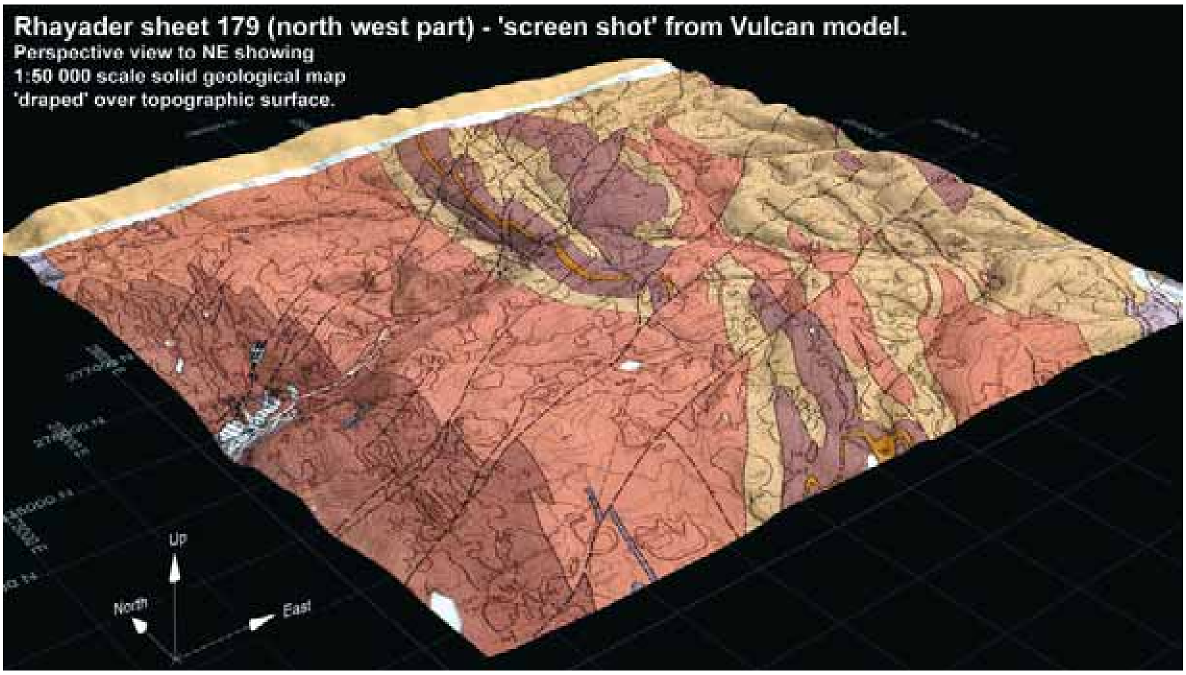
Minor intraformation lithological subdivisions were omitted. The model clearly illustrates, and allows immediate understanding of, an area of complex structural geology. Geometrical relationships between lithostratigraphical units and fault architecture are demonstrated (especially at depth) in a manner which is almost impossible to deduce purely from examination of the 1:50 000 geological map, and it has internal consistency within fault-bounded blocks. However, it was extremely time-consuming to produce — the lack of sub-surface data meant that all lithostratigraphical modelling had to be manually input and edited by the modeller. The lack of sub-surface control, meant that there was uncertain confidence in the model at depth, other than 'it looks reasonably correct'.

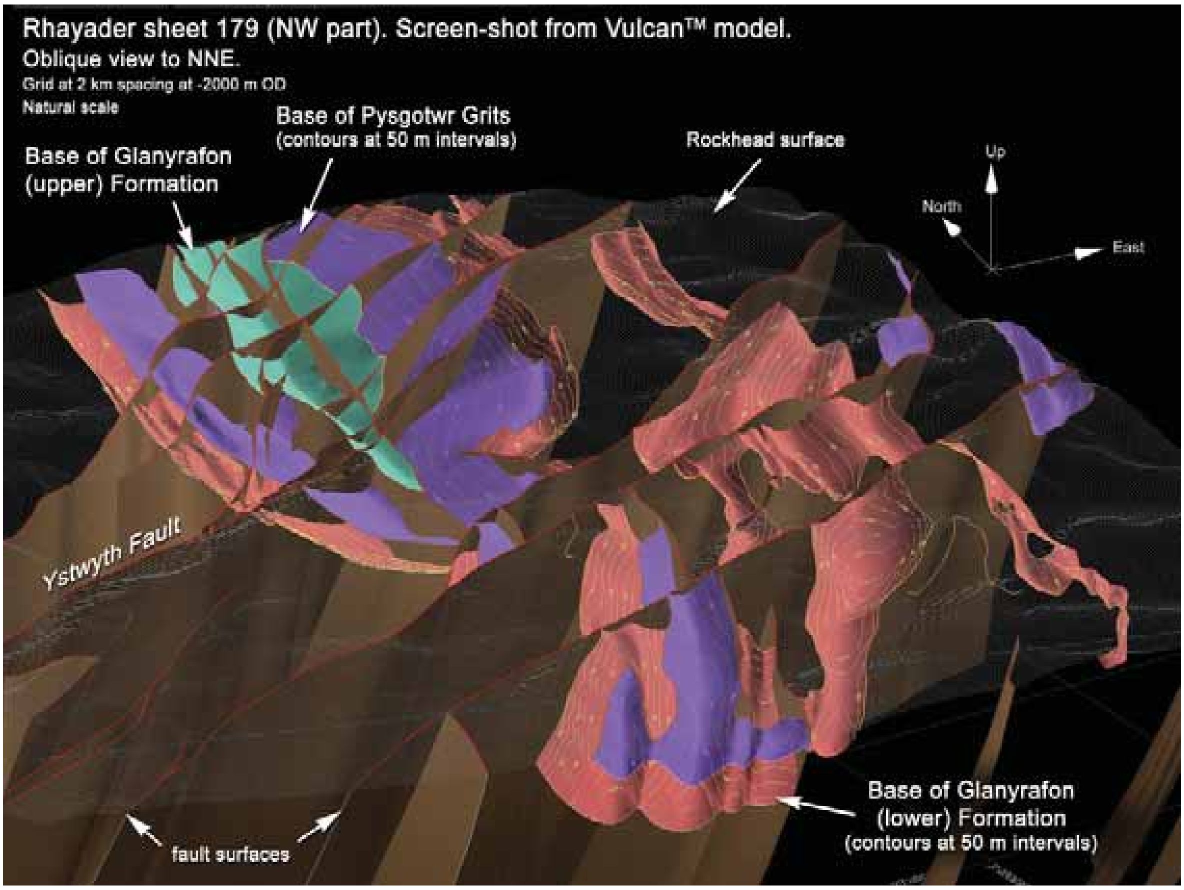
The model was created in the following steps:

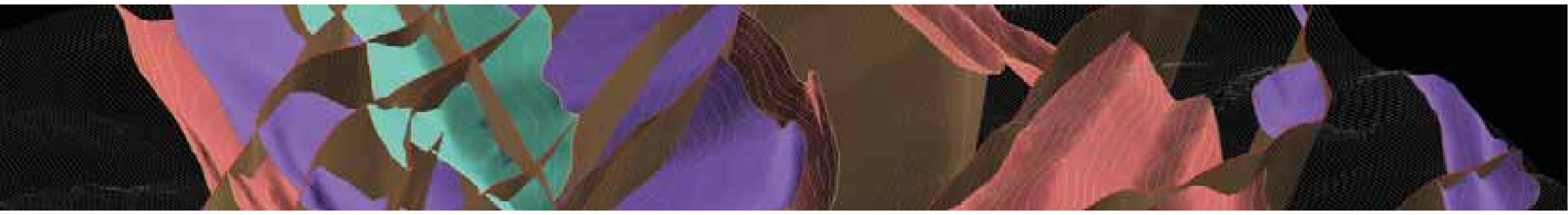
- The DTM was created in both triangulation and grid (25 m spacing) versions.
- BGS DiGMapGB digital geological linework was imported at 1:50 000 scale for both bedrock geology and superficial deposits.
- The superficial deposits linework was registered on to the DTM to generate correct elevations.
- A rockhead surface was generated assuming that the general peat thickness in upland areas is 1 m, which was subtracted from the topographic elevation. In the valley floors, it was assumed that the rockhead morphology approximates to a rounded 'glaciated valley' profile, infilled with till and alluvium deposits up to 20 m thick. The location of rockhead was estimated 'by eye' and digitised on-screen as transverse cross-sections spaced between 50 and 200 m. In areas free of superficial deposits, rockhead was taken to be equivalent to the topographic surface.
- The bedrock geology linework was registered on the rockhead surface to generate correct elevations.
- The published geological cross-section was used to generate additional 3D linework.
- The fault system was modelled by projecting fault trace linework into the subsurface at angles of dip depicted on the cross-section, and then creating triangulations to represent the fault plane surfaces.
- The relevant portion of the solid geological map-sheet was georeferenced for 'draping' over DTM and rockhead surfaces for creating 'screen-shots' and presentations.
- The fold axes were modelled as triangulations (as for fault planes), to form a 'fold structure framework' which, together with the fault system model assisted in modelling the folded stratigraphic surfaces.
- To model the main stratigraphic surfaces, a series of cross-sections representing the base were created 'by eye' to make 'reasonable geological sense'. The cross-section spacing varied from 50 m in the structurally complex zones to 200 m in the less complex areas. The digitised profile lines were discontinuous at fault plane intersections, thus representing the throw on the faults. The fault-bounded blocks were modelled separately, because many of the faults were found to be high-angle reverse faults with a consequent overlap (in plan view) of the stratigraphical surface close to the fault plane.



The Welsh model

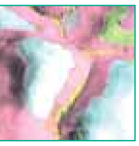






Future support & development

As this report shows, a large amount of work has taken place that will allow the BGS to face a future focussing on representing the geology of UK in 3D. A continuing expenditure of time will be required to ensure that the databases are maintained, that the applications are de-bugged and kept up-to-date with developments in technology. As new relevant concepts arrive, they should be incorporated into the framework. That will need commitment and time. We need to ensure that we understand and communicate the quality of our models and interpretations, so that their limitations are appreciated. This will ensure that additional work can be effectively focussed on refining the models, and not on reinforcing what we already understand.



More than that, there is enormous potential for characterising the solid earth better in terms of predicting the properties of the rock-mass for more and more specific requirements. There is the challenge in understanding and characterising geological processes, both in the geological time-scale and in the human time-scale. In other words, we can present an understanding of how geological structures developed and what that can tell us about the generation of resources and potential for geological hazard. We can also predict how we might be influencing subsurface properties by introducing fluids or pollutants and how neotectonic processes might affect our environment.

LithoFrame

The provision of a strategic geological and geo-environmental knowledge-base across the UK landmass is the core function of the BGS. Critical to this is the provision of a modern, 3D national geological framework, focussing principally on the zone of human interaction (the shallow geosphere). The BGS has traditionally produced two-dimensional geological maps series at scales of 10k, 50k and 250k, which are usually thought of as 'fit-for-use' at these scales. The provision of digital 'map' information has followed the same pattern (DigMap10, DigMap50, etc). A series of systematic models will form the 3D geological framework representing Britain's geology: they will be called LithoFrame.
These 3D models will also be 'fit-for-use' when viewed at various scales (as with maps) and the for each scale, there will be a suitable depth for the model. It is proposed, therefore, LithoFrame should comprise a series of 3D model products at specified resolutions or 'scales', each of which would essentially be a subsurface extension of DiGMap at that scale. The scale indicated is the maximum scale for which the model is 'fit-for-use'. The specification of each, and the strategy for constructing them are summarised in the table opposite.

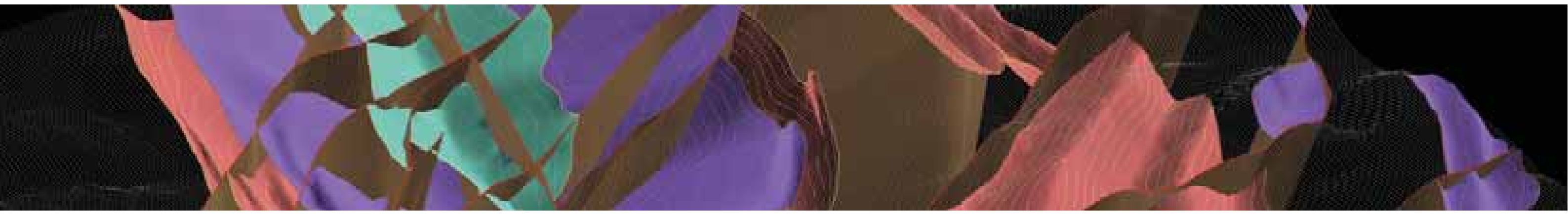
The development of LithoFrame will provide the opportunity to enhance and extend currently acquired geotechnical datasets and to attribute the 3D lithostratigraphical framework with information that will both create new opportunities for understanding the geological processes that control the variation in these basic properties and allow users to assess their site-specific data in an appropriate context.

SCALE: The ratio or relationship between a distance or area on a map and the corresponding distance or area on the ground, commonly expressed as a fraction or ratio. A map scale of 1/100 000 or 1:100 000 means that one unit of measure on the map equals 100 000 of the same unit on the earth.

RESOLUTION: The detail with which a map depicts the location and shape of geographic features. The larger the map scale, the higher the possible resolution. As scale decreases, resolution diminishes and geological boundaries must be smoothed, simplified, or not shown at all; for example, small areas may have to be represented as points.

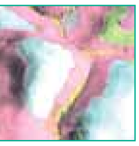
LithoFrame

	LithoFrame1M	LithoFrame250	LithoFrame50	LithoFrame10
Proposed coverage (long term)	Entire onshore and UK Continental Shelf	Entire onshore and UK Continental Shelf	Onshore UK and adjacent nearshore areas	Major urban and development areas; areas of complex near-surface and classic geology
Tile size	Single tile	100 x 100 km	20 x 20 km	5 x 5 km
Grid resolution of component surfaces	1 km	500 m	100–200 m	50–100 m
Depth	50 km	10–15 km	1–5 km	100–200 m or base of superficial deposits if deeper
Uses	Public awareness of science; education; national/international scientific collaboration	Popular science, overviews for the energy, groundwater and waste management sectors; deep structural investigations	Land-use planning; major infrastructure development; energy and mineral resources; groundwater; waste management	Site specific planning and development control; detailed ground investigat-ions for engineering, resource and environment applications
Key baseline datasets	DiGMap625 digital geology; deep seismic profiles; regional magnetic and gravity data; deep boreholes	DiGMap250 digital geology; seismic profiles; magnetic and gravity data; deep boreholes	DiGMap50 digital geology; seismic profiles; ground and airborne geophysical data; boreholes; deep mine data	DiGMap10 digital geology; detailed ground and airborne geophysical data; boreholes and site investigations data; mine plans
Stratigraphical resolution	Stratigraphical systems and deep crustal layers to the Moho; no superficial deposits	Bedrock groups; superficial deposits undivided	Bedrock and superficial formations	Bedrock and superficial members, other important beds and markers
Faulting	Major faults defining discrete terrains and structural elements of UK geology, typically with displacements of several kilometres	Faults defining regionally significant displacement of several hundred metres	Displacements exceeding 50 m. Amalgamated where spacing is less than 200 m	Displacements exceeding 10–15 m. Amalgamated where spacing is less than 100 m
Igneous rocks	Major plutons such as the SW England and Lake District batholiths, covering several hundred sq km in areal extent and linked at depth	Plutons with outcrops and/or subcrops of at least 10 sq km; major extrusive successions of regional extent	Intrustions with outcrops-subcrops of at least 5 sq km; thick composite lava and pyroclastic deposits	Minor intrustions; individual lava flows and pyroclastic deposits



3D visualisation facility

Since the inception of the DGSM programme, visualisation technologies have developed, allowing users to examine spatial models in many ways. These include advances in 3D visualisation technologies that are based on stereographic projection of images in ingenious and often complex ways variously called 'data caves', HIVEs, or 'visualisation domes'. They have become important in engineering design, aircraft pilot and high-speed driver training, and in immersive cinema. Many oil companies use them as a routine part of designing a reservoir drilling campaign. We realised that the principle could be relatively cheaply and simply configured into a very powerful environment for demonstrating our results from modelling, and for exploring and sharing geoscientific ideas.



The 3D visualisation facility at Keyworth.

Humans take for granted the ability to see in 3D. We use stereoscopic vision to measure range by triangulation. Each eye sees a different view of the world and the visual system fuses these images into one 3D stereo view. In virtual reality stereoscopy, separate left- and right-eye images are created by the computer and projected onto the screen; special glasses are used to fuse the images — fooling the mind into believing it is seeing 3D.

With active stereo left- and right-eye stereo images are presented by alternating the display at a rate of about 115 Hz. The glasses have infra-red controlled LCD light shutters which mask the right and left eye in synchronisation with the projector.

Two or more projectors can be used and their outputs merged onto wider or curved screens. These are called multichannels systems. The projectors can be in front of the screen, in which case the audience might shade part of the image or in the rear, with the image reversed for viewing.

The image can be moved around by the operator from the computer. The viewer themselves can be equipped with tracking sensors on their glasses which monitor their head position and direction of viewing; the image responds which enhances the feeling of reality — this is called 'immersion'.

We have installed a single-channel active stereo system running on a standard desktop PC, with dual-head graphics card and plenty of memory. It uses a Christie Digital Mirage DLP 4000 lumen projector, projecting onto the rear of a flat screen measuring 4.5 m x 2.5 m, and a wireless ultrasonic/inertial controller and head-tracker for manipulating the models. This simple configuration has removed the need for calibrating multichannel and mirror systems, making it simple to maintain but giving enough computer power to manage our larger models.

The virtual reality facility has immediately had an impact on the ability to visualise and understand models. There is little doubt that similar facilities will become the norm for working with models and for presenting them to our customers.

Using the 3D visualisation facility at Keyworth.

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