The capture and dissemination of integrated 3D geospatial knowledge at the British Geological Survey using GSI3D software and methodology.

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Abstract

The Geological Surveying and Investigation in 3 Dimensions (GSI3D) software tool and methodology has been developed over the last 15 years. Since 2001 this has been in cooperation with the British Geological Survey (BGS). To-date over a hundred BGS geologists have learned to use the software that is now routinely deployed in building systematic and commercial 3D geological models. The success of the GSI3D methodology and software is based on its intuitive design and the fact that it utilizes exactly the same data and methods, albeit in digital forms, that geologists have been using for two centuries in order to make geological maps and cross-sections. The geologist constructs models based on a career of observation of geological phenomena, thereby incorporating tacit knowledge into the model. This knowledge capture is a key element to the GSI3D approach. In BGS GSI3D is part of a much wider set of systems and work processes that together make up the cyberinfrastructure of a modern geological survey. The GSI3D software is not yet designed to cope with bedrock structures in which individual stratigraphic surfaces are repeated or inverted, but the software is currently being extended by BGS to encompass these more complex geological scenarios. A further challenge for BGS is to enable its 3D geological models to become part of the semantic web using GML application schema like GeoSciML. The biggest benefits of widely available systematic geological models will be an enhanced public understanding of the subsurface in 3D, and the teaching of geoscience students.

Keywords

3D Geological Modeling, 3D Visualization, Systematic Geological Surveying, Knowledge Capture, Geoscience Education.

1. Introduction

1.1 Background

Three-dimensional geological modeling has developed dramatically over the past 30 years from contouring and gridding techniques using mainframe computers through to PC based geological modeling software developed mainly for the hydrocarbon and mining industry. These tools were developed with large sums of money available in the relevant industries and therefore often only deal with very specific geological scenarios and data types. CAD and GIS tools were also customised to deal with geological environments, but this often led to a convoluted multi-software solution which became hard to use and implement as a single working tool. As well, there are many geostatistical and database techniques available to carry out interpolations between geological measurements especially on a regional scale. These methods are often unsuitable for unevenly distributed data and may not properly cope with the qualitative and interpretative element of geology. In summary, none of these tools and associated methodologies are aimed at the working practices of survey geologists nor the types, quantity and quality of legacy data typically found in national or state geological survey institutions.

Many geological survey organisations worldwide have started to implement varying software systems and methodologies to facilitate a migration, from a 2D paper-based survey to a 3D digital service provider of geoscientific information (Jackson, 2005) These include software packages, the most prominent of which appear to be Gocad [1] and Geomodeller [2] that are both widely used in geological survey organisations in Australia, Europe and North America.

These and many other software systems and methodologies used for geological modelling are extensively documented elsewhere, for example in Turner (1991), Mallet (2002, Rosenbaum and Turner (2003) and Zanchi *et al*. (In Press), and references therein.

1.2 The BGS approach

In the 21st century BGS envisages 3D geological models as the logical next step from the traditional 2D geological map and hence as a core output from its future programme. BGS has over 200 trained surveyors and investigative geologists (including urban, coastal, hydrocarbon, hydrogeology, and mineral specialists) who produce geological maps and interpretations using varied field data capture techniques and legacy datasets at a series of pre-defined scales. The aspiration of the Survey is that all these scientists should be able to build models of the geology they investigate to common specifications and where possible to do this using common software tools and methodologies. Hence modeling must not be a black art that can be practiced by just a few highly skilled specialists. Therefore a major part of the BGS requirement for modeling software is for an easy to use, simple, intuitive package that can be placed affordably on the desktop of a large number of geologists after brief training. The software must be capable of modeling the majority of geological terrains encountered in the UK at acceptable productivity rates and capable of dynamic revision when new data or interpretive insight becomes available.

As mentioned above, several technically excellent but complex modeling packages are on the market and some of these have been used very effectively by BGS for specialised tasks. These include EarthVision and Gocad for regional stratigraphic modelling and Vulcan for detailed mineral exploration. BGS also uses Surfer and Rockworks for site-specific geological, geophysical and hydrogeological visualization. But as Perrin *et al*. (2005) commented the current modeling methodologies "*do not allow the use of a knowledge-driven approach*" and are not conducive to rapid model updating and revision. For a Survey organisation such as BGS they also offer the significant disadvantages of very high costs (see also Rosenbaum and Turner, 2003; Turner and Gable, 2007) and maintenance for concurrent use of up to 50 people a day. The roll out of a complex package would also involve a massive training requirement and investment of staff time and create abundant highly trained modeling specialists (see also Perrin *et al*., 2005). Experience in BGS gained through the DGSM project (Smith, 2005) has shown that modeling rates achieved in some of these complex packages are slow. Clearly other solutions are necessary for the systematic and routine needs of a large survey organisation such as BGS.

The Geological Surveying and Investigation in 3 Dimensions (GSI3D) software tool and methodology has been developed over the last 15 years. The initial development was in response to the recommendations of a study at the NLfB (Niedersächsisches Landesamt für Bodenforschung - Soil and Geological Survey of Lower Saxony), by Binot and Röhling (1994). In response the software was designed as a tool for modeling shallow superficial-Quaternary sequences using a cross-section-based approach (Hinze *et al*., 1999; Sobisch 2000). From 2001-05 the British Geological Survey (BGS) became a test bed for the accelerated development of the tool and methodology, initially through the Digital Geoscience Spatial Model (DGSM) project (Smith, 2005; Hatton *et al.*, 2005). This project was tasked with examining available software solutions and recommending a way forward for BGS as it migrates from a mapping to a modeling culture both in terms of working practices and outputs. Take-up of GSI3D in systematic surveying, urban, coastal and engineering studies soon followed and early examples of these are given by Culshaw (2005).

GSI3D is now routinely deployed in building systematic 3D models in the UK (referred to by BGS as LithoFrames, see below) and as part of commercial contracts for clients such as the Environment Agency of England and Wales (EA), the UK Water Sector and Local Government. The implementation of GSI3D within BGS has only been possible because, by 2000, the Survey had digital geological maps at scales effective for modeling available for almost the whole UK (Jackson and Green, 2003). At the same time, licensed, nationwide high-resolution Digital Terrain Model (DTM) coverage had become available. Databases of both, borehole index and downhole data supported by corporate dictionaries for lithological and stratigraphic terminology had also been established. Virtually all BGS's paper records had been scanned and most legacy map data had been geo-registered. The retrieval and subsequent use of all this data was aided by well organised data indices and associated metadata. GSI3D now successfully utilizes all this data combined with the wealth of geological knowledge trapped within the scientists' brain, to produce 3D geological models.

2. The GSI3D software and methodology solution

The following section describes the varied baseline datasets used in modeling and the overall system architecture of the software at BGS. The success of the GSI3D methodology and software is based on the fact that it utilizes exactly the same data and methods, albeit in digital forms, that geologists have been using for two centuries in order to make geological maps and cross-sections.

2.1 Data formats used in GSI3D

a) Topographic maps and Digital Terrain Models

Raster images of topographic base maps, air photos and satellite images can be imported into GSI3D as geo-registered JPEGs. Existing elevation models such as the land surface (DTM), bathymetry, "Rockhead", watertables, or unconformities can be loaded into GSI3D as standard ASCII grid files.

b) Boreholes classified lithologically and interpreted stratigraphically

Digital borehole data is extracted into two distinct tabulator-separated ASCII files from the corporate Single Onshore Borehole Index (SOBI) and Borehole Geology (BoGe) databases using a Data Portal (see below). Corporate dictionaries and stratigraphic lexicons are established for coding boreholes.

The borehole index file is downloaded from SOBI as shown below, containing the unique borehole ID, location in x, and y in our case with respect to the British National Grid and start (collar) height (z) relative to UK Ordnance Datum. GSI3D displays drill logs according to their own start height, although the user has the option to fix all logs to the DTM if that is preferred.

Unique Borehole ID	Easting (x)	Northing (y)	Start (Collar)Height (z)
SE64SW23.	123456	123456	11.22

The borehole log file shown below contains information on the depth to base of each of the identified units down the borehole. This can be geological information from BoGe formatted via the Data Portal or any other downhole database organised into tab separated columns as shown below. The log must be complete from the surface downwards and not intermittent; intervals of core loss are coded as absent data not left blank.

Unique Borehole ID	Depth to base of Unit (metres)	Lithostratigraphic Unit Code (BGS Lexicon)	Lithology Code (BGS Rock Classification)
SE64SW23.	1.23	ALV	CZ
SE64SW23.	4.56	LGFG	SV
SE64SW23.	7.89	LOFT	CSZV

c) Geological map data (linework and measurements)

BGS currently holds all geological map data in proprietary ESRI format. Therefore points, lines and polygons can be loaded into GSI3D as ESRI shape files. In future it is planned to import all geological linework via GeoSciML exchange formats. As GSI3D currently deals only with superficial and unfaulted bedrock environments complex structural measurements are not supported, however, as mentioned below (see section 4.1), GSI3D is currently being extended and adapted to model such environments and incorporate the necessary structural information.

d) Sections

Geo-registered planar vertical and horizontal sections (defined as slices in GSI3D) can be integrated for common visualization with the stratigraphical/lithological dataset in the section window and/or with the cross-section network and the structural model in the 3D window. In BGS this data includes all scanned marginalia from published map sheets and geophysical data such as electric mapping and ground penetrating radar measurements.

e) Colour and symbol legend

A legend file is loaded to assign colours and textures to the map polygons, borehole logs, and correlated sections, This ASCII tabulator separated text file contains an RGB value for each code used in the Generalised Vertical Sequence (GVS) file below. The presence of a corporate colour scheme is helpful, as it allows the modeller to quickly visualize any anomalies and discrepancies in their correlation.

f) Numerical point measurements

Geo-referenced numerical point measurements such as geotechnical test and chemical analyses can also be loaded and visualized in conjunction with drill logs and cross-sections. This data is loaded as ASCII text files that are manually created from measurements captured in a wide variety of proprietary softwares.

2.2 Geological Rules – Topology

The GVS file controls the order in which the geological unit can occur at any point (stratigraphy) and rejects any relationships drawn in sections that do not correspond to this pre-determined order. The GVS file is a tabulator- separated ASCII text file and forms the backbone of the GSI3D project. It is produced by the modeller, evolving throughout the project and finally contains all units in their correct and unique super-positional order, as the order itself defines the 'stack' that is calculated to make the 3-D geological model. The essential elements of the GVS file are shown here:

Name	Id	Stratigraphy	Lithology	Genesis	Free text
Dtm	0	DTM	DTM		DTM for the site
Alv	10	ALV	CZ	Fluvial	Overbank Alluvium
Rtdu	20	RTDU	SV	Fluvial	River Terrace
Loft	30	LOFT	CSZV	Glacial	Basal till
Kes	40	KES	S	Fluvial	Periglacial Braided River
Rcg	50	RCG	S	Marine	Tidal shelf
Lens_top	-100	LOFT_L	SV	Glacial	Till lens top
Lens_base	100	LOFT_L	SV	Glacial	Till lens base

Name	contains the model code that provides the link to the correlation lines and geological units in the stack; it must be unique for each layer. The order from top to bottom must be the stratigraphic order of the entire model area.
id	The ID column is used internally to define the stratigraphic sequence of units and cross-cutting bodies such as lenses and intrusions.
Stratigraphy	This field, and subsequent fields, (here lithology and genesis) are used to provide the link to the legend file. Any of these fields can be selected to colour up the model. This example GVS also contains an optional extra column for free text or notes.

It is apparent from the above rules that at present the GSI3D software is not designed to cope with reverse faults, recumbent folds and other structures in which individual stratigraphic surfaces are repeated or inverted in a vertical sequence. However, as already mentioned the software is currently being extended to encompass these more structural complex geological scenarios.

2.3 Software methodology

GSI3D is programmed in Java and works with four windows namely map, cross-section, 3D and borehole log window (Figure 1). The four windows are dynamically linked, which means that changes in the map or section window result in instant updating of all the other windows.

(Figure 1)

The GSI3D tool and methodology is based on a single simple philosophy - the construction of geological sub-surface models has to proceed with an understanding of the complete geological sequence and the likely geomorphological evolution of the study area (see also Fookes, 1997).

The processes that form the geological units and their subsequent arrangement can not currently be simulated accurately by computers. Hence these processes can only be captured and expressed by the sensible construction of geological boundaries by experienced geologists, in particular where data is sparse or of poor quality (see Lemon and Jones, 2003; Wu *et al*., 2005; Kaufmann and Martin, 2008). The geologist draws such boundaries based on a career of experience and observation (Kessler and Mathers 2004, 2006). The use of such tacit knowledge is also recognised as important for model construction by Varnes (1974), Fookes (1997), Turner (2003), Jones *et al*. (2004), Turner and Gable (2007).

Since the origins of geology two basic methods have been used to show geological relationships - maps and cross-sections, both of which depict a representation of the geological sub-surface arrangement. The GSI3D methodology imitates this classic way of working by providing the geologist with firstly a tool for drawing cross-sections and secondly one for digitising the distribution envelope (outcrop plus subcrop) of every geological unit in the stack (Figure 2). Once this is achieved the 3D spatial model is calculated by triangulation, interpolating between the correlation line nodes in sections and along geological boundaries. Importantly, the integrity of the model is directly related to the alignment and frequency of the cross-sections that together build a fence diagram. Geologists have traditionally favoured fence diagrams to show complex sub-surface arrangements (Mathers and Zalasiewicz, 1984; Mengeling 1999; Sobisch, 2000).

(Figure 2)

In many Quaternary and sedimentary settings it is only possible to correlate the geometry of individual units when the topography, surface mapping and borehole logs are viewed in relation to each other in a 3D environment. This is because superficial deposits, such as glacial, fluvial and coastal deposits, are rarely identifiable through fossils or unique lithological markers. In these environments 3D modeling is virtually impossible without a cross-section approach.

GSI3D forces the geologist very effectively to check the numerous intersections between the cross-sections to produce a properly connected and internally consistent framework. At the same time the model is totally consistent with the surface and subcrop mapping of the geologist. For the actual model calculation a digital terrain model (or any other capping surface) and the GVS file (see above) must be present. Another key strength of GSI3D is that if the GVS and a DTM are present the cross-section displays the evolving 3D geology instantaneously.

Interpolating between the x,y,z nodes along the sections and those along the limits of the envelopes of each unit produces a series of triangulated irregular networks (TINs), each corresponding to the base of one of the geological units present. The use of TIN structures to describe geological objects is described by Turner (2003). GSI3D deploys a bespoke Delaunay-triangulation based on a Quad-edge algorithm (Green and Sibson, 1978). The creation of 3D objects, tops and base combined (a.k.a. volumes, shells) is then simply achieved by capturing the base(s) of the immediately overlying units (or the DTM where the unit is at outcrop). Where units extend beyond the project boundary vertical walls are inserted to close the 3D object. The resulting object is the logical equivalent to a polygon describing a geological unit in 2D.

GSI3D employs a bespoke TIN-cutting algorithm to make instant calculations of all tops enabling the emerging model to be calculated iteratively and tested throughout model construction. Equally a very fast TIN-TIN intersection algorithm allows the calculation of predicted outcrop patterns using high resolution DTMs.

In the same way the finished model can be quickly revised in the light of new data or realization. So it is not essential to save the finished model, but simply the four components from which it is calculated: namely cross-sections and envelopes in xml format, DTM and GVS. Automatic generalization to produce lower resolution models is possible by using Boolean operations on correlation lines and envelopes after defining combined sets of units in the GVS file.

In summary, the benefits of GSI3D are that it simply replaces existing analogue working practices of geologists with buttons in software, so it is easy to train people to use the software leading to widespread acceptance and implementation as demonstrated by users at BGS. Furthermore GSI3D is programmed to work quickly and in a truly dynamic way, allowing it to be part of a systematic, iterative and interpretative survey process.

3. Applications

This section describes two working examples that have been enabled by the implementation of GSI3D into the work process at BGS. The first is part of the BGS vision to build systematic models for the whole of the UK, the second describes the delivery of detailed spatial model to external customers to solve a particular problem.

3.1 LithoFrame Models and Resolutions

BGS is now embarking, on a program to systematically build 3D models, at the four principal resolutions 1:1 Million, 1:250 000, 1:50 000 and 1:10 000 mentioned above. These models will be constructed across the entire country to standards developed from the last 5 years of research into systems and methods for 3D modeling (Smith, 2005). The products, known collectively as LithoFrame are described more fully on the BGS website [3]. These LithoFrame models will be structured and attributed to meet the needs of a wide range of applied users, and ultimately, will take the place of the traditional geological map. However, this will only happen if the models are produced on a national scale, at realistic costs, and are made available and accessible to the user community (Jackson, 2005; Turner, 2006).

Linkage between the varied scales and resolutions is produced by a series of progressively more detailed nested stratigraphies within increasing size of scale and detail shown in a theoretical example in Figure 3. For example at 1 Million scale the UK Cretaceous might be indicated as a single unit, whereas at 1:250 000 scale the Lower Cretaceous and the Upper Cretaceous (Chalk Group) might be depicted. At 1:50 000 scale it is usually possible to show the 8-9 Formations that together comprise the Chalk Group sequence and at 1:10 000 scale individual marker beds and facies can be included. The overriding principle is that in each case the overall top and base of the packet of strata remains the same notwithstanding the simplification and smoothing needed at smaller scales.

(Figure 3)

Any geological project is created with its’ own aims and objectives. For example in the systematic surveying of terrain the procedures and outputs are pre-determined and the sizes and scales of outputs are consistent. However many surveying or modeling projects are commissioned by a client with very specific needs.

Additionally the availability and quality of geological data, geological linework, borehole logs, and geochemical sample points is never evenly distributed. For example a 1:10.000 scale geological map sheet in a major urban area may have thousands of registered borehole records and site investigation reports whereas a similar size area in a remote upland National

Park might contain no boreholes whatsoever. It is thus apparent that models produced with GSI3D will vary in scale, detail and resolution.

Three basic categories of investigation (Overview, Systematic, Detailed) are suggested here in Table 1, but in reality even these are part of a continuum from the most general assessment of the geology down to a very detailed investigation on the scale perhaps of a quarry for planning extraction and reserve estimation or the site investigation for a major engineering structure.

3.2 An applied 3D model – Manchester, UK

The main outputs of BGS have always had their main use in the decision-making process. In the UK the use of 3D geospatial models by customers as a replacement for analogue and 2D digital products is increasing every year. As with many new digital products however, the BGS is facing a lag between offering innovative products and the level of IT capacity and equipment in use by its customers. It is hoped that the provision of models encrypted within the LithoFrame Viewer will help overcome these effects so removing the customer's need to invest in software and training to analyse models.

Experience has shown, that 3D geological models will only be used where the traditional 2 dimensional geological map or GIS no longer supports the decision making process of the customer. The majority of models so far commissioned by clients are for management, protection and regulation of water supplies. This is because geological spatial models naturally connect with another area of geo-computing, that of the groundwater modeling community. Legislation such as the EU Water Framework Directive (European Union, 2000) has increased the need to understand not only the geometry of the main aquifers but also the structure and composition of the overlying Quaternary deposits and soils.

The Permo-Triassic sandstones beneath central Manchester and Salford form part of the Manchester and East Cheshire aquifer which is a significant groundwater resource for both industrial and public water supply. Historic abstraction in some parts of the aquifer has resulted in falling groundwater levels and the localised upflow of saline water. However, recent changes in patterns of abstraction in response to industrial policy, and the local policies of the regulatory Environment Agency of England and Wales (EA) have resulted in the recovery of water levels in some areas. However, there remains a level of uncertainty as to the sustainable level of abstraction in the aquifer. This is complicated by the abandonment of coal mines to the north of the area that may potentially affect flow patterns and groundwater quality within the aquifer. In order to fulfill its statutory duties to manage and protect water resources, the Agency is undertaking a regional groundwater study to quantify the sustainable resources of the aquifer. This has involved development of a conceptual model of the aquifer that will provide the framework for future resource management. The study is being undertaken principally by Environmental Simulations International (ESI).

One of the key areas of research relates to the rate of recharge, which is at present poorly constrained but is an important parameter as it effectively defines the available water resource. It also, to some extent, defines the vulnerability of the aquifer to pollution. Most recharge reaches the sandstone aquifer via the thick superficial deposits that cover much of the region. Understanding the complexities and hydrogeological performance of these superficial deposits is therefore paramount if estimates of recharge are to be realistic.

It was against this background that the EA requested BGS to provide a 3-dimensional model of the superficial and artificial deposits of a 15 x 5 km block in the Manchester area (Figure 4), to investigate the potential hydrogeological impact of the highly variable superficial deposits on groundwater recharge to the Permo-Triassic sandstone aquifer (Kessler *et al*., 2004, Lelliott *et al*., 2006).

(Figure 4)

The overall objective of the study was to use a 3D model of the superficial deposits to examine potential groundwater-surface water interactions Using GSI3D the project utilised the existing 1:10,000 geological map data and 7000 boreholes (mainly site investigations), to characterise the relationships within the Quaternary sediments and identify potential hydrogeological pathways between the surface water bodies and the deeper sandstone aquifer. The best way to appreciate the likely flow paths was to produce targeted sections through the 3D model. Additionally to these a series of thematic maps were generated using standard GIS technology. These maps show domains of potential groundwater vulnerability following the approach advocated by McMillan *et al*. (2000). This methodology is now stored as a GIS query and so it can be replicated for future studies. In addition the study provided the customer with ASCII grids of the tops, bases and thicknesses of all the superficial geological units together with their hydrogeological properties. These were then used as the basis for the numerical groundwater flow model using MODFLOW (ESI Ltd, 2006).

The study showed that in the Manchester conurbation the potential pathways for pollution and recharge are mainly located along the Manchester Ship Canal and adjoining areas where bedrock is at outcrop or close to surface. Thick till in blue and, largely concealed glaciolacustrine silts and clays in purple, protect the aquifer below the adjacent Trafford Park area, however; there is the potential for lateral migration via the outwash sheet deposits in red which are locally in contact with the bedrock aquifer in orange-brown. The eastern part of the modelled area is dominated by a thick Devensian till (blue), which is likely to reduce recharge and vulnerability here. However, incised rivers cut through the till into the bedrock and are often infilled with man-made deposits (in grey); these are likely to offer recharge pathways and may lead to leaching of any associated contaminants into the aquifer.

3.3 GSI3D in a wider context

At BGS GSI3D is part of a much wider set of digital systems and work processes, which together make up the entire workings, or cyberinfrastructure, of a modern geological survey (Figure 5). The following paragraph describes briefly the technologies and methodologies from capturing and modeling through to storage and delivery of geological knowledge and data. A more detailed description of the components and the modeling workflow as a whole is presented by Smith (2005).

(Figure 5)

Most of BGS's legacy data holdings are already available digitally as vector or raster data. New data gathered as part of a systematic or responsive survey are captured with digital field notebooks and can then be downloaded via remote access from the field to the corporate databases. Data is served to the modelers using a web-based data portal based on ArcIMS technology. This system provides the user with a map based interface to select all raw data by type and distribution. All data is converted to GSI3D compatible formats using Java scripts and is consequently delivered to the modeler's desktop in a compressed archive file. The data is then visualized and co-validated in GSI3D, working with temporary model files in a project workspace located on the Small Area Network. During the modeling process the geoscientist may update the corporate databases with new interpretations using customized Microsoft Access and web-based front ends. A new set of data can then be downloaded and used in the next iterative modeling phase. On completion of a model a set of metadata needs to be completed before all component model files are loaded into ORACLE for archiving.

Customers can obtain geological models in several ways. Geological models can be served via the web in form of Flash animations and 3D PDFs giving the users a pre-view of the model and some interactive functionality. The availability of high-performance graphics cards combined with OpenGL on virtually all modern PCs also allows more advanced 3D visualization of geological models in real time via rich client solutions. For this purpose BGS uses a Java based 3D viewer that forms a sub-set of the GSI3D software called the LithoFrame Viewer. A small example model and a user manual are served here [4]. In this application the user can create synthetic boreholes and sections, change the theme properties of the model, create contour maps as well as explode the model for detailed analysis (Figure 2). These calculations are performed on the user's PC so only the data has to be transmitted via the web or CD-ROM. Data can also be delivered to customers in many other requested formats such as scattered x,y,z points, ASCII grids, ESRI shapes and grids and VRML surfaces.

The future challenge for BGS is to enable its data holdings to become part of the semantic web (Jackson, 2007). This means converting data into self-descriptive schema using XML (Apel, 2005, Mello and Xu, 2006), or GeoSciML (Cox *et al*., 2005) and making them visible to the outside world and understandable to humans and computers alike. Only then will we have achieved the full transfer of knowledge envisaged by the US National Science Foundation (2003) and the UK Office of Science and Technology (2006).

4. Conclusions and Outlook

4.1 A survey in change

BGS has produced paper maps for 170 years and these often require geological expertise to understand them fully. The originators' spatial ideas, models and concepts have never been fully captured in their full 3D context, and so, until now, have been lost to the science and to users. This consequential loss of knowledge has been enormous. The use of tools like GSI3D, now enables earth scientists to easily construct systematic 3D models that incorporate all usable data for a given area. Such models have the advantage of being dynamic - capable of instant revision as soon as new data becomes available. Just like their predecessors, geological maps, these models have a wide range of applications (Kessler *et al.*, 2005) and are suitable for interrogation using GIS-based analytical tools to produce thematic and bespoke outputs. For example, for the hydrogeologist the combination of all impermeable layers in the stacked model can, produce maps of total aquitard thickness and the degree of aquifer protection, so useful in groundwater recharge, pathway and pollution studies. Similarly models enable the thickness and volumes of aggregate resources or mineral ore-bodies and their overburden to be contoured, and so derive thickness ratios to define cut-off points for exploration or extraction. Furthermore interrogation of the model at any given point will provide the user/customer with an automated borehole prognosis for the site. A geological section can be generated along any specified slice through the model (horizontal as well as vertical), for use in linear route planning or tunneling (Ozmutlu and Hack, 2003; Culshaw, 2005). These systematic models represent the building blocks of the 3D architecture of Britain's geology. We are now ready, due to methodological and technological advances, to translate and extend William Smith's map fully into the third dimension to produce solid models of Britain's geology.

Based on the acceptance of the software and the increasing demand for 3D models across a wide range of geological settings in the UK, BGS has now embarked on a 3-year R&D project to extend the capability of GSI3D. This will include functionality to model more complex bedrock environments including structures such as normal, reverse and scissor faults, fold axes, overturned strata, and cross-cutting intrusive bodies. The intention however is to maintain the simple intuitive approach of the software and methodology to enable deployment to all BGS's scientists. The LithoFrame Viewer is being upgraded in parallel in order to deliver these more complex models to clients.

4.2 Geology in education

Just as Mogk *et al.* (2004) suggest, the authors believe that on of the most important beneficiaries of this step change of delivery of geological information will be the general public and in particular geoscience students and teachers. We envisage 3D geological models will become much more educationally informative than their forerunners - geological maps, and in addition will enable those with less honed 3D thinking than experienced survey geologists to fully appreciate often complex spatial relationships. This is because the real 3D relationships can now be demonstrated, explained and studied in a virtual environment. Eventually the benefit will be a greatly enhanced general appreciation of the subsurface arrangement of rocks and soils and their role in the supply of needed resources, the construction of infrastructure and the storage of the waste.

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Figure captions and Table

Figure 1. GSI3D software interface with interactive map, cross-section, 3D and borehole window ***(Colour requested in hardcopy).***

Figure 2. The model building workflow (1A-1E) in GSI3D and example analytical outputs (1F-H) that can be derived from the calculated model within the LithoFrame Viewer. The model shown comprises some 1200 sq km of the Sudbury-Ipswich-Felixstowe area of southern East Anglia, UK. (from Kessler and Mathers 2006). ***(Colour requested in hardcopy).***

Figure 3. The LithoFrame concept and linkage between resolutions ***(Colour requested in hardcopy).***

Figure 4. 3D geological model of Manchester area (15 times vertical exaggeration) ***(Colour requested in hardcopy).***

Figure 5. The position of GSI3D amongst the other elements of the BGS cyberinfrastructure.

Type of Survey or Investigation	Overview	Systematic	Detailed – Site specific
Section Spacing	several km	0.5-1.5 km	< 500 m
Section Length	Tens of kms	5-10 kms	<5 km
Density of Coded Boreholes	Less than 1 per square kilometre	Commonly 5 - 10 per square kilometre	Often hundreds per square kilometre
Mapping Level	Major Groups and Formations only	Formations and Members, big lenses	Members and thin individual beds and lenses, Artificial Ground
Modeling speed (excluding data preparation**)**	Up to hundreds of square kilometres a day	Up to 20 square kilometres a day	< 2 square kilometres a day
Scale	Compatible with 1: 250K or 1:50K geological linework	Compatible with 1:50K or 1:10K geological linework	Compatible with detailed site plans at larger scales than 1:5K
Modeling Output	Often just sections and an open fence diagram.	Computation of geological objects and surfaces for export to GIS.	Computation of geological objects and surfaces for export to GIS.
Uses	Useful for education, visualization and overviews (e.g. catchment characterisation), first-pass assessments	Builds a 3-D model stack for interrogation in site selection, route planning, resource assessment, recharge and aquifer studies etc.	Detailed 3-D model for analysis of thickness, volumes, flow paths providing bed-by-bed stratigraphy for use in Urban and Quarry planning, and site investigations.
Minimum Unit thickness	5 metres	1 metre	0.1 metres

Table 1. Scales of Investigation using GSI3D

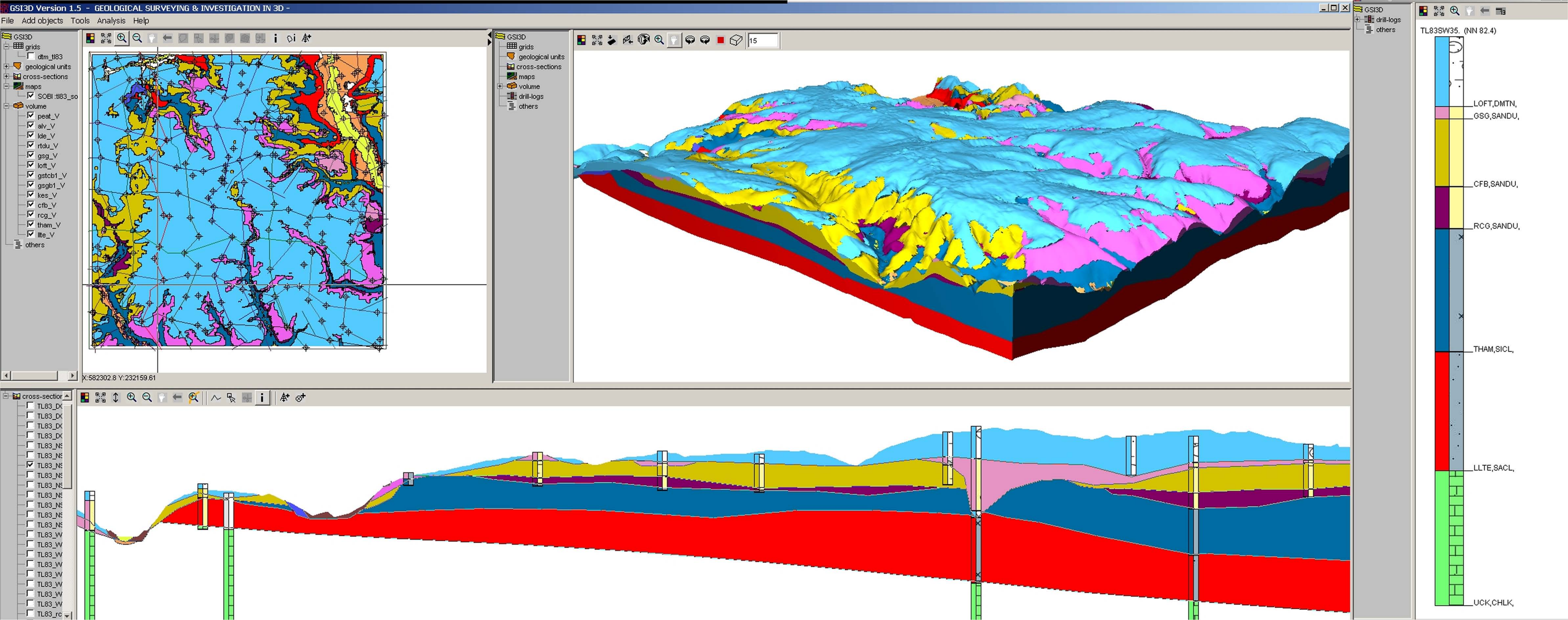
Footnotes

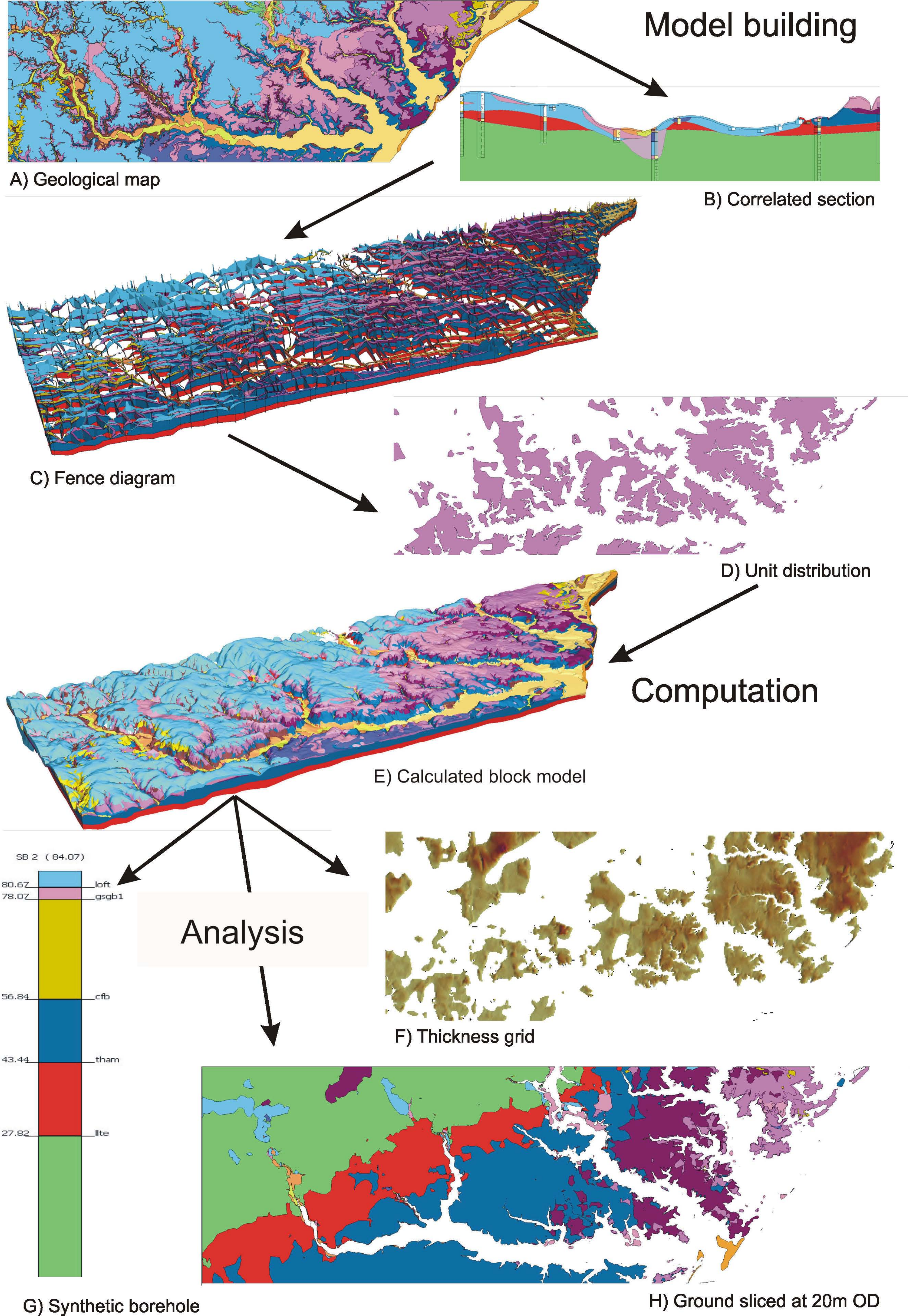
[1] Gocad 2008. Website of Gocad http://www.earthdecision.com/

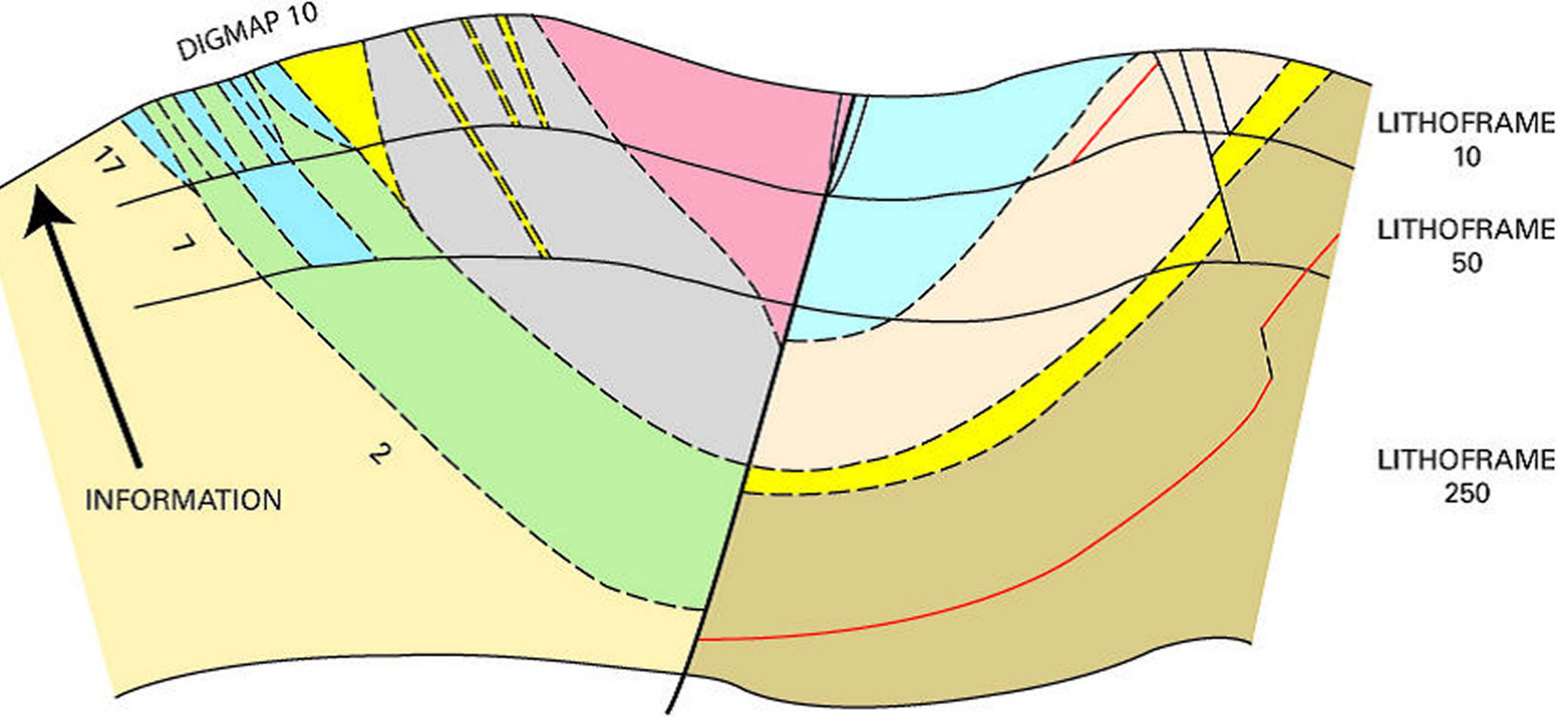
[2] Geomodeller 2008. Website of 3D Geomodeller http://www.geomodeller.com/geo/index.php

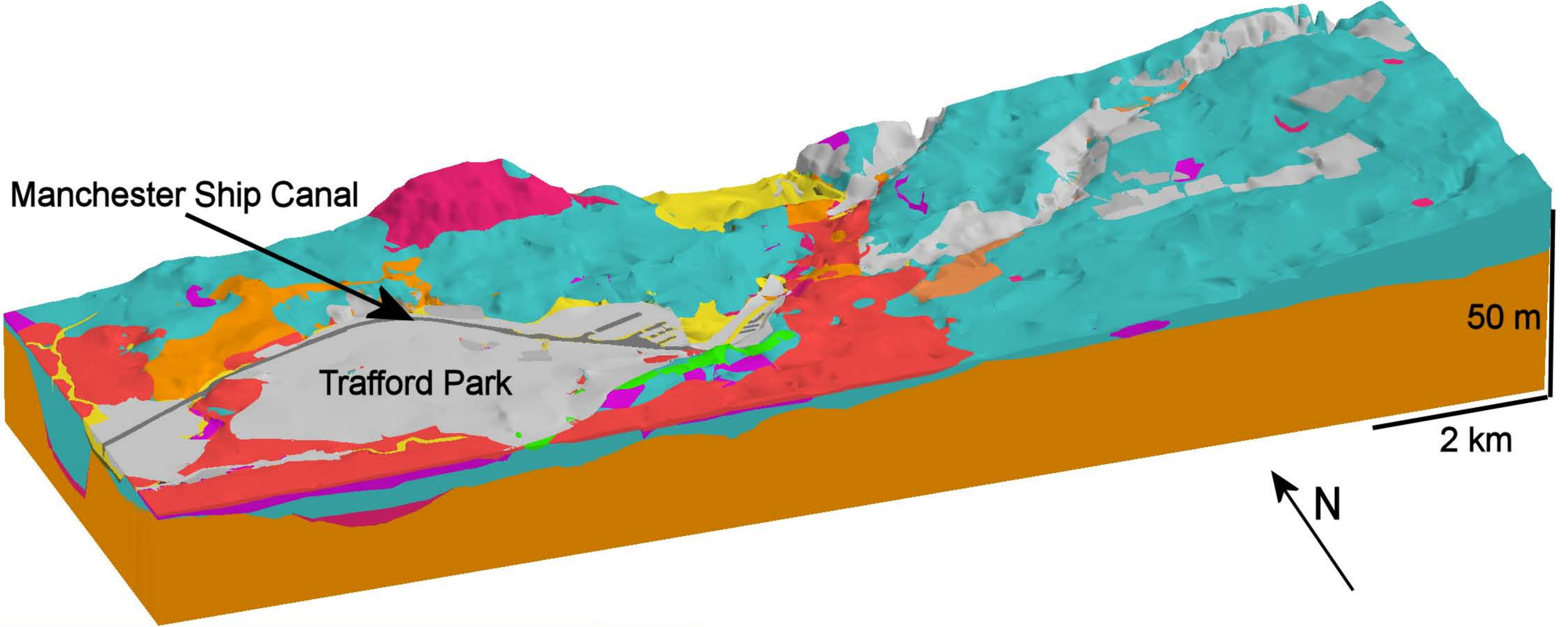
[3] BGS 3D modeling webpage http://www.bgs.ac.uk/3dg

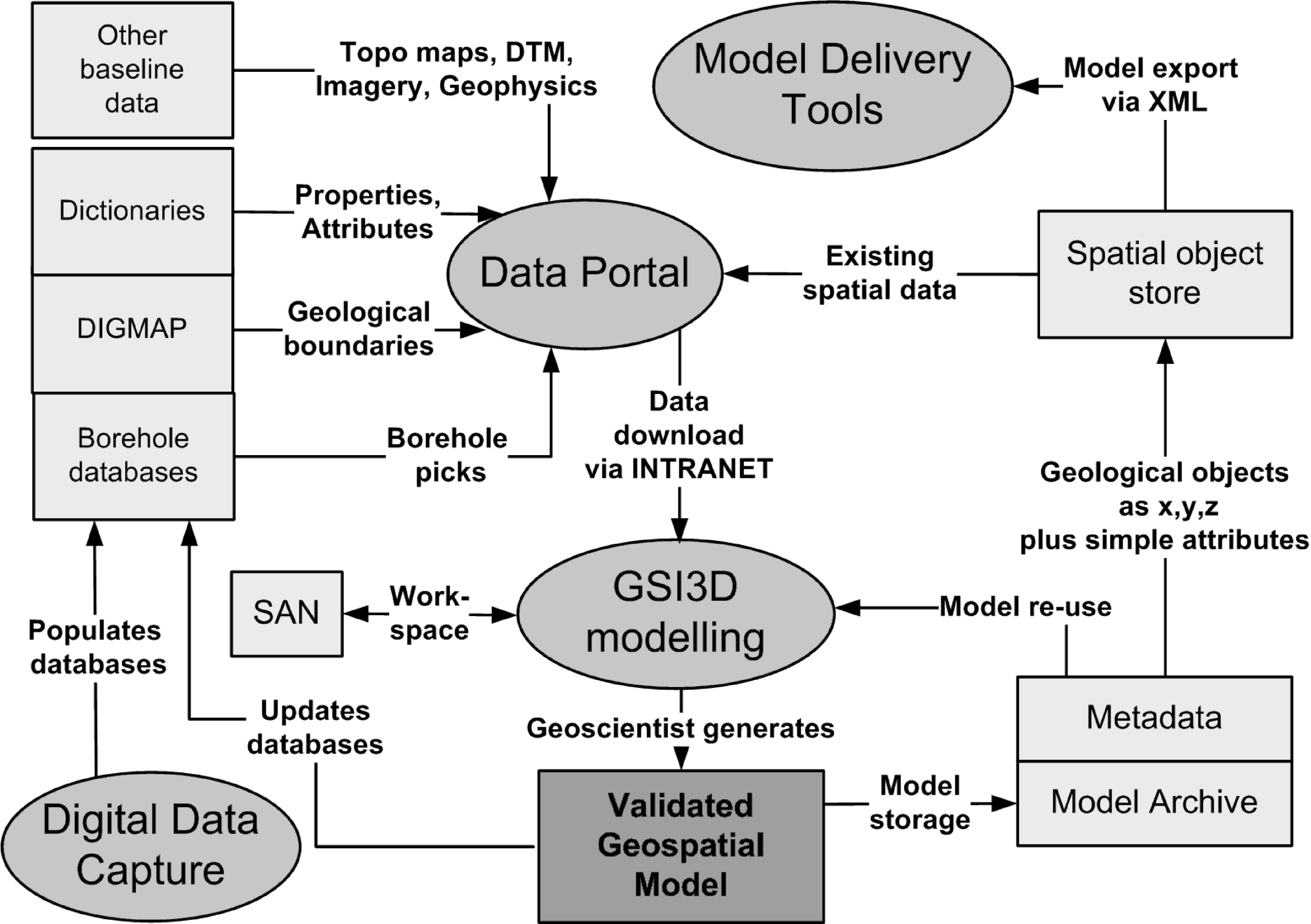
[4] Geological model download http://bgs.ac.uk/science/thamesgateway/3dModels.html


GSI3D Version 1.5 - GEOLOGICAL SURVEYING & INVESTIGATION IN 3D -
File Add objects Tools Analysis Help
GSI3D
grids
dtm_tl83
geological units
cross-sections
maps
SOBI :tl83_so
volume
peat_V
alv_V
lde_V
rtdu_V
gsg_V
loft_V
gstcb1_V
gsgb1_V
kes_V
cfb_V
rcg_V
tham_V
llte_V
others
X:582302.8 Y:232159.61
drill-logs
TL83SW35. (NN 82.4)
LOFT,DMTN,
GSG,SANDU,
CFB,SANDU,
RCG,SANDU,
THAM,SICL,
LLTE,SACL,
UCK,CHLK,
cross-section


Model building
A) Geological map
B) Correlated section
C) Fence diagram
D) Unit distribution
Computation
E) Calculated block model
Analysis
SB 2 (84.07)
80.67
loft
78.07
gsgb1
56.84
cfb
43.44
tham
27.82
llte
F) Thickness grid
G) Synthetic borehole
H) Ground sliced at 20m OD


DIGMAP 10
LITHOFRAME 10
LITHOFRAME 50
LITHOFRAME 250
INFORMATION
17
7
2


Manchester Ship Canal
Trafford Park
50 m
2 km
N



Other baseline data
Topo maps, DTM, Imagery, Geophysics
Model Delivery Tools
Model export via XML
Dictionaries
Properties, Attributes
Data Portal
Existing spatial data
Spatial object store
DIGMAP
Geological boundaries
Borehole databases
Borehole picks
Data download via INTRANET
Geological objects as x,y,z plus simple attributes
SAN
Work-space
GSI3D modelling
Model re-use
Populates databases
Updates databases
Geoscientist generates
Metadata
Model Archive
Model storage
Digital Data Capture
Validated Geospatial Model

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