Geoscience Data Journal
Open Access

GB3D – a framework for the bedrock geology of Great Britain

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This study was funded by the British Geological Survey and Environment Agency of England and Wales in 2009–2012.

In 2011, the British Geological Survey (BGS) decided to begin the assembly of a National Geological Model (NGM) from its existing and on-going geological framework models comprising integrated national crustal, bedrock, and Quaternary models. The bedrock component is the most advanced of these themes and comprises both the calculated models and a complementary network of cross sections that provide a fence diagram for the bedrock geology of Great Britain. This fence diagram, the GB3D_v2012 dataset, is the subject of this article and is available in a variety of formats from the BGS website (www.bgs.ac.uk) as free downloads. It complements the existing 1:625 000 scale map sheets published by BGS utilizing the same colour schema and geological classification. The 121 component cross sections extend to depths between 1.5 and 6 km; they have an aggregate length of over 20 000 km, and they are snapped together at their intersections to ensure total consistency. The sections are guided by the existing BGS geological framework models where they cut through them; they also take account of the vast wealth of published data on the subsurface structure of Britain both from BGS and in the literature. Much of this is in the form of cross sections, contour maps of surfaces, and thicknesses (isopachs). The fence diagram has been built in the Geological Surveying and Investigation in 3D (GSI3D) software. Utilizing the cross sections and the coverages of the geological units simple 3D volumes can be calculated for the less deformed sedimentary strata. It is envisaged that this dataset will form a useful educational resource for geoscience students and the general public, and also provide the bedrock geology context and structure for regional and catchment scale studies.

Geosci. Data J. (2014), doi: 10.1002/gdj3.9

Received: 2 January 2013, revised: 1 May 2013, accepted: 22 August 2013

Key words: 3D modelling, geology of GB, bedrock geology, cross-sections

Dataset

Identifier: doi:10.5285/f60c6923-0bd2-4469-bc7a-9c0775453ac8
Creator: British Geological Survey
Title: National Bedrock Fence Diagram of Great Britain - GB3D_v2012
Publisher: British Geological Survey
Publication year: 2012

Introduction

Over the past 25 years, the British Geological Survey (BGS) has produced three-dimensional (3D) geological framework models at a variety of resolutions both to satisfy the needs of clients and also in the Survey's role as the national provider of geoscience data and information increasingly as 3D digital products. These framework models can be thought of as 3D geological maps describing the geometry and subsurface distribution of geological units akin to those depicted on the traditional printed geological map outputs. Over time, many software packages have been used to construct these models, many of these were designed primarily for use in the mining and hydrocarbons sectors and so are not always ideal for widespread use in a geological survey context. The individual models have to date been built to be stand alone, or as parts of small series built to a single specification. They range from a national 1:1 million resolution model extending to the base of the Crust at 15–25 km depth (Mathers, 2011; Mathers *et al.*, 2011) to detailed models designed to resolve shallow subsurface issues at a site-specific or local scale.

Between 2000 and 2005, BGS investigated modelling software options and designed stores capable of holding the built models as part of the Digital Geoscience Spatial Model (DGSM) project (Smith, 2005). In terms of software, the principal outcome was the decision to focus on two main software packages for future 3D geological model construction. The established hydrocarbon package GOCAD® would continue to be used to build basin-scale models of bedrock geology based mainly on deep wells with wireline logs, and seismic data; whilst shallower models of Quaternary, Anthropocene, and structurally simple bedrock geology would be constructed using the emerging Geological Surveying and Investigation in 3D (GSI3D) package developed partly in house at BGS.

In 2011 BGS decided to begin the assembly of a National Geological Model (NGM) from existing and future models, this would involve the following:

- Pulling together existing framework models.
- Designing quality assurance (QA) and approval procedures for these and future models including provision of adequate metadata documentation.
- Storing the completed models in a systematic way both as frozen native-format models and, in future, in deconstructed form as part of a newly commissioned store of individual geo-referenced and attributed geological objects (sections, surfaces, unit extents, faults, etc.).

The NGM delivers the following:

- Geospatially correct representations of geological units in 2D and 3D.
- Scale-independent construction, storage, and dynamic management, i.e. multi-scaled, storing of the best available interpretation at any point.
- National in scope, and in time with seamless onshore and offshore coverage.
- A generic geology based interpretation (as for existing 2D map outputs), fit for any purpose.
- Independence from specific software platforms by using generic interoperable file formats that will stand the test of time.
- Model attribution via corporate codes for geological units and their bulk properties that can be dynamically linked to lexicons, dictionaries, and other supporting databases and libraries.

Separate crustal, bedrock, and Quaternary themed models are planned at present, the first two of these share a common first-order stratigraphic classification. Over time, the base of the Quaternary model will form the cap for the bedrock and crustal models where resolution requires this level of detail.

The bedrock component of the NGM is currently the more advanced of these three themes and comprises two types of objects:

1. Existing framework models and modelled surfaces produced at 1:50 000–1:1 million resolution containing variable levels of stratigraphic detail. These include:

   A A 1:1 million national crustal model that extends down to the Moho and is based largely on the data in Whittaker (1985).

   B A series of regional and basin-scale models at a nominal 1:250 000 resolution that for the most part extend to a few kilometres depth (Mathers *et al.*, 2011). These mainly cover Carboniferous and younger sedimentary basins with hydrocarbon potential.

   C Many more detailed and localized models at a 1:10 000–1:50 000 resolution extending to depths of a few hundred metres. Some of these more detailed models have been built up as consistent tiles to cover larger areas of 2–3000 km^2 for example in the London Basin, southern East Anglia, and Glasgow.

All these models are now undergoing checking and QA procedures prior to their acceptance into the NGM and storage in their native formats.

2. A complementary network (fence diagram) of cross sections (Figure 1) based on the 1:625 000 scale bedrock geology map sheet schema (Figure 2) has been constructed in GSI3D. These sections are guided by the existing models where they slice through them and elsewhere provide a national bedrock framework. This fence diagram is the GB3D_ V2012 dataset. Using the fence diagram to define the subcrop extent of units and combining these with surface outcrops yields 2D coverages for each unit. To date, the fence diagram has been mainly used for visualization and illustration, although calculated first order 3D volumes have also been generated for the younger and more continuous sedimentary units from the cross sections and coverages. The GB3D_ V2012 dataset is the subject of this article.

1. Building the GB3D fence diagram

The GB3D_v2012 fence diagram covers the onshore area of Great Britain (England, Scotland, and Wales) and the Isle of Man. It comprises 121 cross sections extending to depths varying between 1.5 and 6 km with a total linear section length of over 20 000 km (Figure 1). The sections utilize the published bedrock geology and colour schema of the BGS 1:625 000 scale bedrock map sheets of UK North and UK South (British Geological Survey, 2007a,b; Figure 2). The geology of these two map sheets is described in two accompanying booklets (Jackson, 2008; and Stone, 2008 respectively).Some of the detail on the published map sheets particularly in relation to faulting, minor intrusions, and lithological variations within individual units have not been included within the fence diagram sections.

The initial fence diagram build during 2009–2010 was funded by the Environment Agency of England and Wales (EA), and reported by Schofield *et al.* (2012). This phase of the development comprised 41 cross sections with a total linear length of 5500 km confined to England and Wales. In 2011, this initial network was extended to Scotland, and the earlier

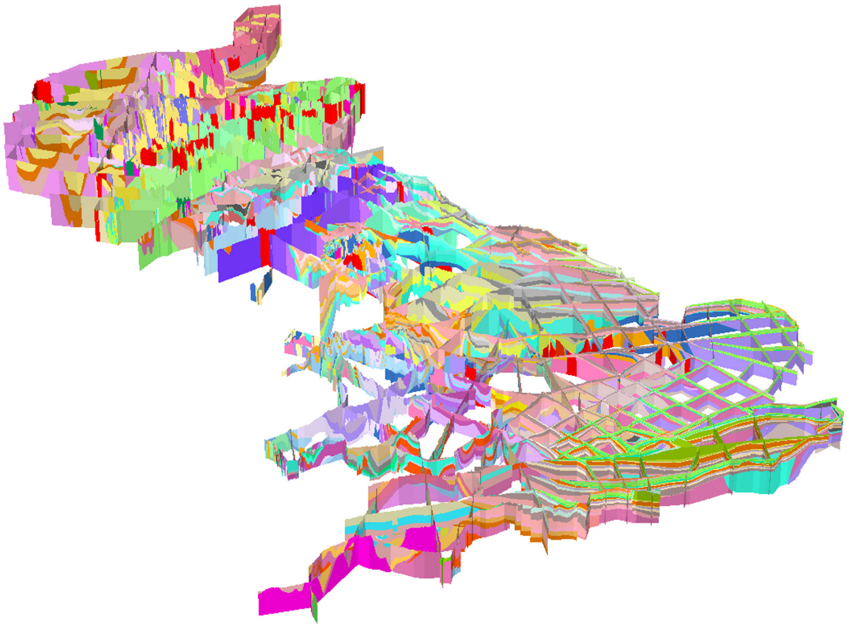

Figure 1. The GB3D_v2012 fence diagram.

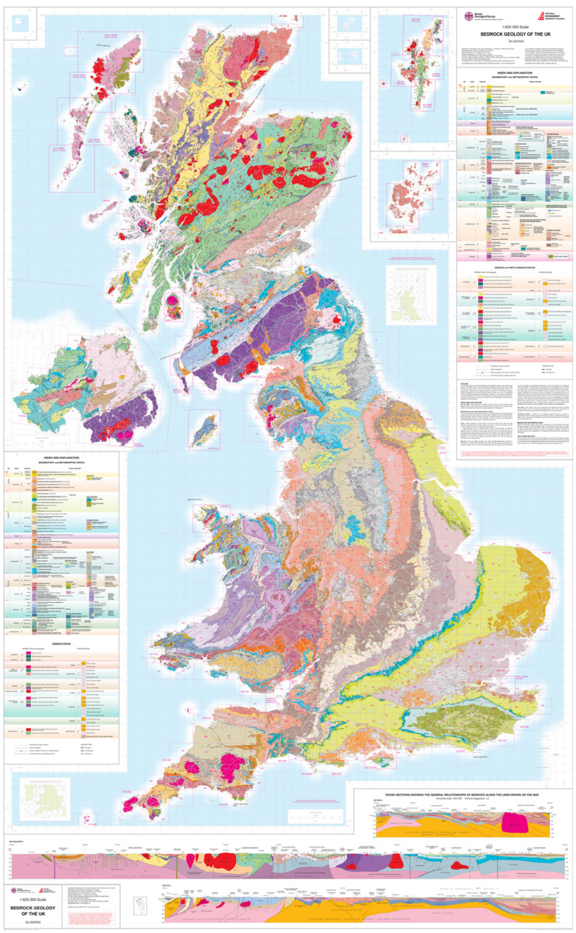

Figure 2. Printed version of the BGS 1:625 000 scale geological data combined from the two component map sheets. Contains Ordnance Survey data © Crown Copyright and database rights 2012.

coverage was densified. Additional sections were also aligned along the coast to bound the coverage and provide the easily recognizable outline of Great Britain paving the way for offshore expansion of the model. Sections in northern Scotland were continued across the Minch to the Outer Hebrides and similarly to Orkney but at present the Shetland Isles have not been incorporated. In 2012, with further funding from the EA, a few additional sections were inserted into the framework for England and Wales, while others were extended in length or deepened in key sedimentary basins. This enhancement comprised part of a study to provide a risk screening tool for the EA to help them gauge possible impacts of shale gas extraction on aquifer security (Mathers *et al.*, 2012a).

The latest expanded version of the fence diagram, named the GB3D_v2012 dataset has been released together with a brief accompanying BGS metadata report (Mathers *et al.*, 2012b). It provides a framework which locks down the bedrock geology of Great Britain and is now likely to change materially only as a result of new data, revised stratigraphy or rock-type classification and new concepts of structural geology. A similar section-based approach is being applied at the crustal scale to the whole of the UK based on initial work in Northern Ireland (Leslie *et al.*, 2013). The approach will also be deployed to Quaternary deposits across the UK, but here greater challenges exist, due to the thin, discontinuous and variable nature of these deposits, and their complex classification. Together these diverse models describe the BGS NGM, which is underpinned by corporate metadata, lexicons, dictionaries, and stratigraphic framework reports.

2. Data contributing to GB3D_v2012 dataset

2.1. Digital terrain model

The Digital Terrain Model (DTM) used forms the topography along the individual cross sections during their construction and can also be used in the GSI3D software to calculate triangulated 3D volumes of the geological units. During 2009–2010, the DTM was initially extracted from the BGS-licensed national NEXTMap 5 m coverage. A variable grid spacing was been adopted comprising a 250 m spacing along the buffered section alignments and 2500 m in the intervening areas. This was subsequently replaced in 2011 with an overall NEXTMap coverage subsampled to 500 m due to the increase in the number of sections. The current dataset also utilized the Isle of Man Shuttle Radar Topography Mission (SRTM) data sampled as a 75 m grid.

2.2. 1:625 000 scale geological map data

The attributed digital shape file (625k_V5_BEDROCK_Geology_Polygons.shp) of the combined 1:625 000 scale bedrock geology maps (British Geological Survey, 2007a,b) was utilized to provide guidance on the surface outcrop pattern during section construction. In GSI3D this is achieved by displaying the geology as a colour-coded ribbon along the trace of the DTM in section view.

2.3. Geo-referenced images from published literature

Each of the 15 expert regional geologists involved in the section construction was asked to provide a list of key published reference material containing useful 2D and/or 3D geospatial information that needed to be taken into account in the construction of cross sections and the definition of the extents (coverages) of geological units. These items were then scanned and geo-referenced and displayed as raster backdrops as an aide to section and unit distribution construction in the GSI3D section and map view windows.

These sources included the following:

- Regional cross sections from existing published accounts.
- Structural contour plots of stratigraphic surfaces and unconformities as well as contoured isopach (thickness) maps of geological units.
- Sub- and super-crop maps of units present below and above unconformities respectively.

2.3.1. Regional cross sections

In a few cases pre-existing regional scale cross sections were incorporated into the fence diagram. The scan of the original section was rendered in the background of the section view and then used to guide the geologist's interpretation along the line of section (Figure 3).

2.3.2. Structural contour plots

Structural contour plots at a regional scale, sourced from the BGS Subsurface memoir series and other publications were particularly useful and they contributed to significant portions of many cross sections. Shown below, for example, is the contour map of the depth to the Caledonian Unconformity for the southwest Pennine Basin and adjacent areas (Smith *et al.*, 2005; Figure 4). These plots are derived from the interpretation of seismic data fixed against a number of key deep borehole records.

2.4. 1:50 000 scale cross sections from BGS published maps

Many cross sections showing useful 3D information are present on the 1:50 000 map sheet series produced by the BGS. These tend to have a higher resolution stratigraphic classification than the GB3D sections and in addition they are commonly aligned through key deep boreholes within each map sheet. These sections exist as 3D shapefiles that can be trimmed to a short segment straddling the intersection with the GB 3D sections (Figure 5). This enables the intercepts of surfaces from the crossing 1: 50 000 scale sections to be displayed and snapped to in the GB3D section construction as shown in Figure 5. In total data from 130 intersecting sections were used to guide the overall GB3D section construction.

2.5. Legacy 3D model data

Existing 3D Model data were also used extensively in the GB3D cross section construction. This means that the GB3D sections are guided by the built models and together they constitute the data comprising the bedrock component of the NGM. The distribution of these existing models is shown in Figure 6.

Slices through the 3D models were displayed as colour-coded and labelled raster backdrops in the section view to guide construction of the GB3D cross section as shown in Figure 7. In certain cases, the geologist may have overridden or adjusted the model interpretation in particular where the model calculation had provided a jagged or incomplete result.

The surfaces from the 1:1 million scale model (Mathers *et al.*, 2011) which are loosely based on Whittaker (1985) proved to be at too low a resolution to be relied upon. Cuts through GOCAD® LithoFrame 1:250 000 resolution models of sedimentary basins in Northumberland-Solway, East Midlands, Southwest Pennines, Craven, and Weald contributed useful detail. More detailed 1:50 000 and 1:10 000 resolution GSI3D models mainly located in the London Basin, southern East Anglia-Essex, Greater Manchester and

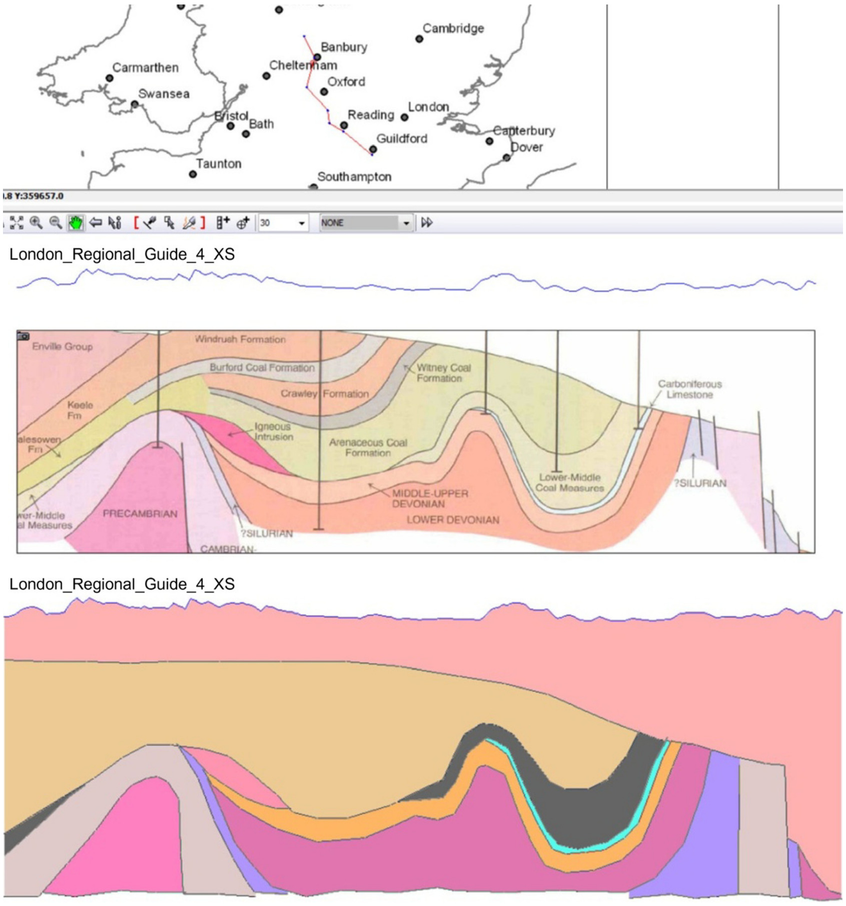

Figure 3. Cross section from Sumbler (1996) showing alignment in red (top) geo-referenced raster image backdrop and DTM (blue) in section view (middle) and drawn GSI3D section (bottom). Vertical Exaggeration is x30. NEXTMap Britain elevation data from Intermap Technologies.

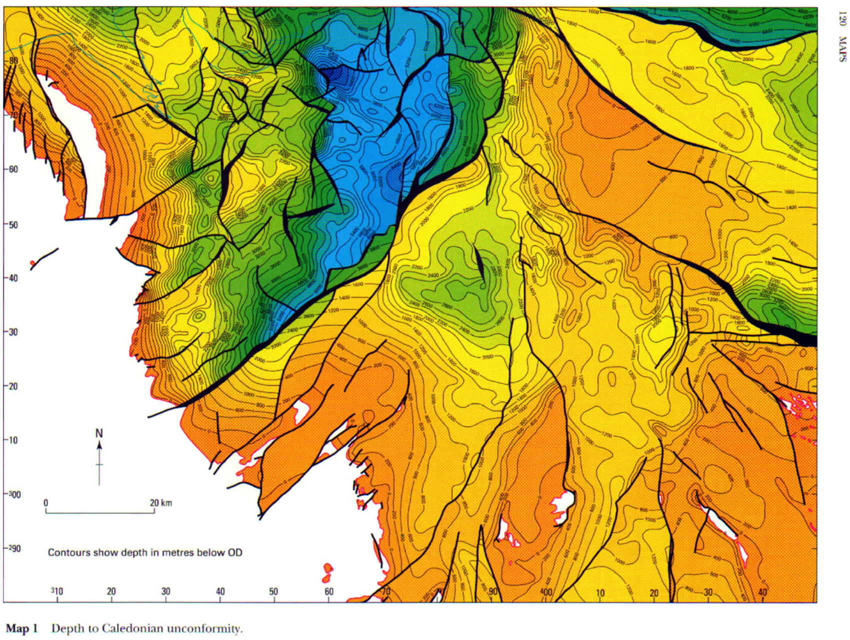

Figure 4. Depth to Caledonian unconformity for the south-west Pennine Basin and adjacent area (from Smith *et al.*, 2005). Contours are in 200 m intervals and are offset by geological faults, shown as black lines where they intersect the unconformity. Contains Ordnance Survey data © Crown Copyright and database rights 2012.

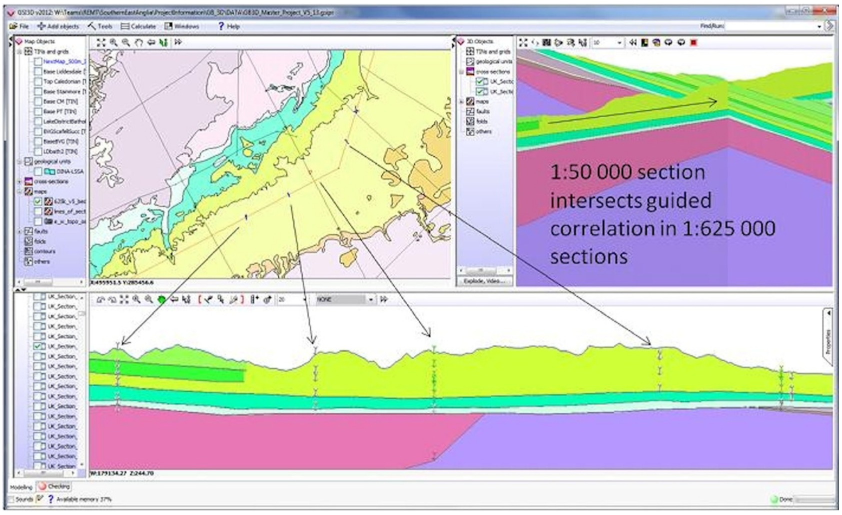

Figure 5. GB3D section shown in red in the map view (upper left) and under construction in section view (below) showing cross ticks from 1:50 000 section intersections as guides (below). Notice the higher resolution stratigraphy available from in the 1:50 000 section in the 3D view (upper right) NEXTMap Britain elevation data from Intermap Technologies.

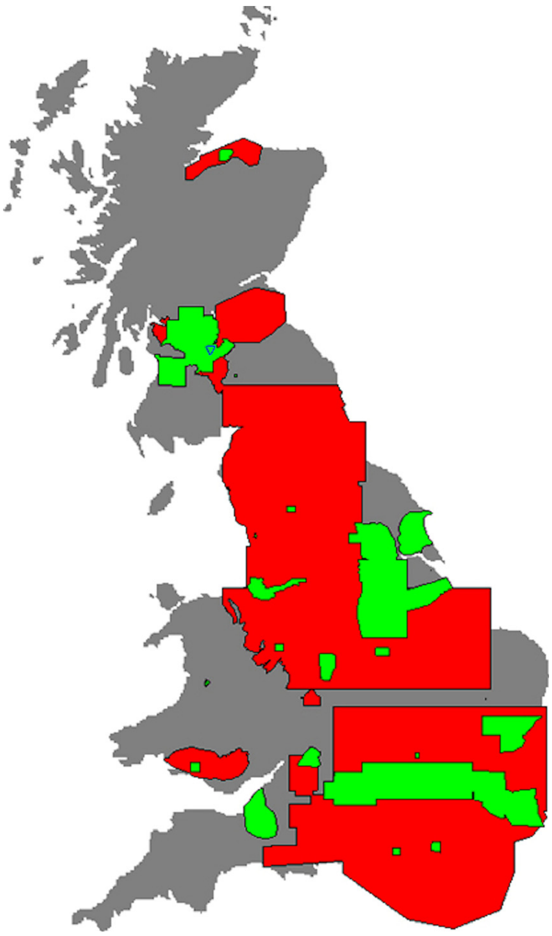

Figure 6. BGS 3D geological framework models at 2012, red shows regional and basin-scale models whereas the green areas contain more detailed shallower models. Green areas enclosed within larger red polygons usually contain models of both types. Contains Ordnance Survey data © Crown Copyright and database rights 2012.

Merseyside, and York are in the main shallow and so were only able to contribute information on the uppermost bedrock units present. Details of the data utilized in the construction of these models are contained in the separate reports and metadata documentation of the individual models and summarized in Mathers *et al.* (2012b) Where multiple resolution models are available the highest resolution (best available interpretation) is normally used.

2.6. Seismic and borehole data

Seismic and borehole data have not been used directly in the construction of the GB3D fence diagram. However, these sources have been extensively utilized in the production of the sections present on 1:50 000 scale map sheets and the various geological models and diagrams that have been interrogated to produce raster backdrops for the GB3D fence cross section alignments. For the first time, all these disparate data sources at varied resolutions have been viewed together in a single workspace and unified to produce a common understanding.

3. GSI3D software

A standard GSI3D workflow (Sobisch, 2000; Kessler & Mathers, 2004; Kessler *et al.*, 2009) was followed for drawing the GB3D sections and constructing the unit distributions (outcrop and/or subcrop) of geological units, referred within the software workflow as envelopes or coverages.

The GSI3D software and methodology (http://www.gsi3d.org) is based on a single simple philosophy – the construction of geological subsurface models has to proceed with an understanding of the complete geological sequence and the likely geomorphological evolution of the study area (cf. Fookes, 1997).

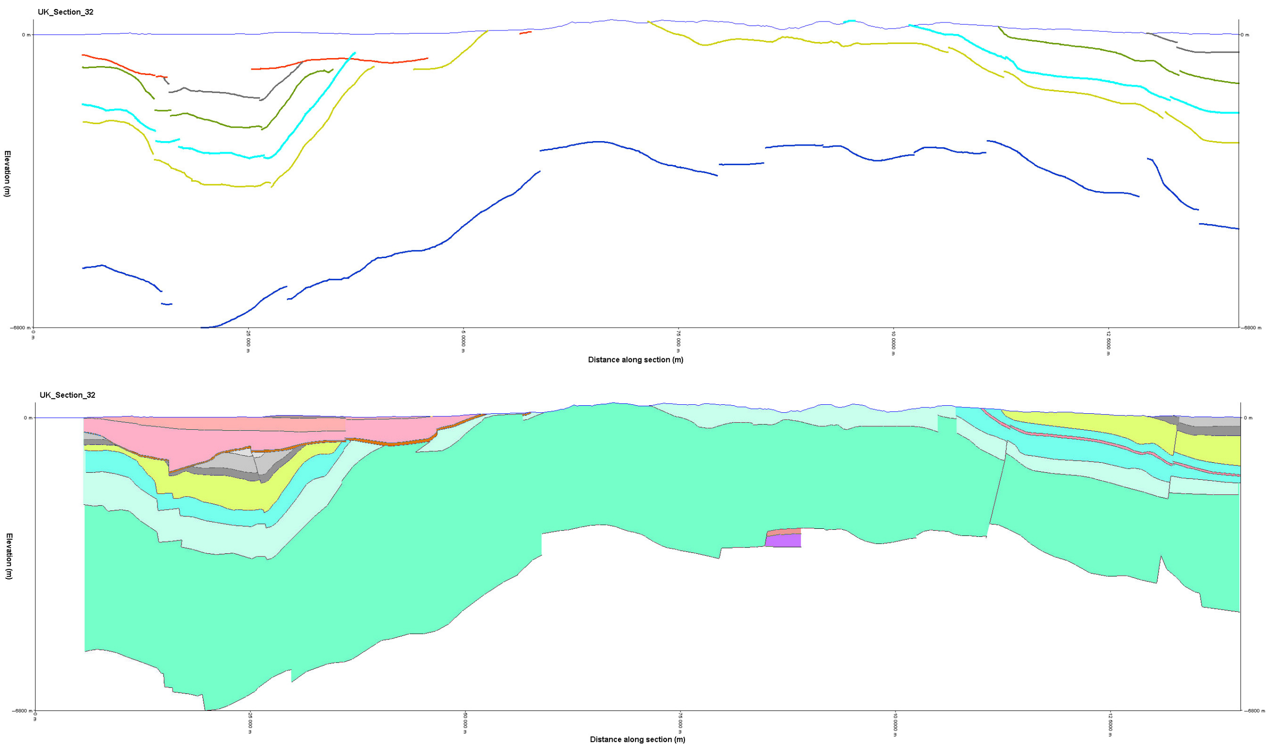

Figure 7. Attributed calculated surfaces from the Northumberland-Solway model (Chadwick *et al.*, 1995) displayed along the line of a GB3D section (above), the constructed section is shown below. Note that faults are shown as offsets in the stratigraphic surfaces. The colour schema for units has not been unified. NEXTMap Britain elevation data from Intermap Technologies.

In simple terms, GSI3D utilizes a DTM, geological surface map line work and down hole borehole data to enable the geologist to construct regularly spaced intersecting cross sections by correlating boreholes and the outcrops–subcrops of units to produce a geological fence diagram of an area (Figure 8(a)–(c)). Mathematical interpolation between the nodes along the sections and the distribution of the units (outcrop plus subcrop) produces a solid model comprised of a series of stacked triangulated objects corresponding to each of the geological units present (Figure 8(d)–(f)). The model cap is formed by a DTM. The 3D spatial model is calculated by Delaunay triangulation interpolating between the correlation line nodes in sections and along the geological boundaries stored as envelopes (Kessler & Mathers, 2004) and illustrated in Figure 9. Once the model is calculated the model can be analysed to produce synthetic logs, horizontal slices at defined elevations, thickness contour plots (Figure 8(f)–(h)), and cross sections along defined routes.

Geologists have traditionally favoured fence diagrams to show complex subsurface arrangements (Mathers & Zalasiewicz, 1985; Mengeling, 1999; Sobisch, 2000). The integrity of the model is directly related to the alignment and frequency of the cross sections that together build a robust, testable fence diagram. The GSI3D methodology and workflow requires the survey geologist to do five things:

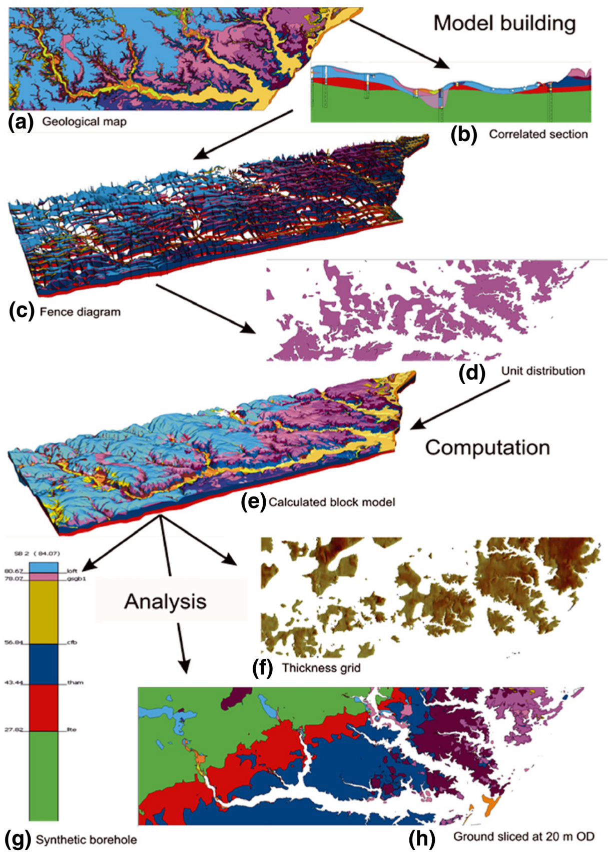

Figure 8. The GSI3D workflow.

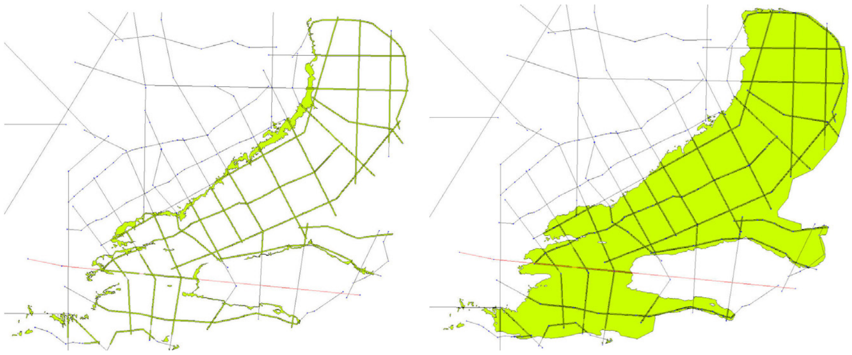

Figure 9. Envelope (coverage) for the Grey Chalk Sub-group: based on the surface outcrop (left) from the 1:625 000 scale map sheet and combined with the subcrop extent defined along the cross sections (left) to form a complete envelope or coverage (right).

- define the stratigraphic sequence (topology rules),
- survey the area to produce a geological map (if none already exists),
- code and classify available boreholes,
- draw cross sections, and
- draw maps of the distribution (outcrop, and/or subcrop) of each geological unit referred to in GSI3D methodology as envelopes (Figure 9).

These tasks are all familiar to geologists and GSI3D simply replicates them in digital form.

The ethos of the GSI3D software is that it replaces the existing analogue working practices of geologists with buttons in software, so it is very intuitive. GSI3D is programmed to work dynamically as part of a systematic, iterative and interpretative survey process. More details are available from the GSI3D Research Consortium website http://www.gsi3d.org/consortium.html.

The current available version of GSI3D, V2011 provides a solution for dealing with artificial (man-made ground), superficial deposits, and simple layer-cake bedrock geology.

4. Project workflow, data management issues, and versioning

During preparation of the original fence diagram during 2009–2010, work on the sections was generally sequential and issues related to model version control were not critical.

However, when a larger number of geologists (up to 15) became involved in the extension and revision of the fence diagram, sometimes simultaneously, careful control and updating of the master version of the GSI3D project was necessary. So data management and model version control procedures were developed (Gow & Terrington, 2012).

This involved a check out– check in system with a single geologist controlling the master project at any one time. If scheduling demanded that several geologists had to work on the sections at the same time each were given distinct geographical limits (i.e. groups of sections) that they were allowed to work on. This also included the design and implementation of a MsAccess 2007 database for tracking the work on individual sections – the GB3D Section Tracker (Figure 10). This database records changes made for each section by geologist, date, cross-section location and has a free text column for a description of changes made (Gow & Terrington, 2012). It forms an invaluable part of the overall project metadata.

5. Multi-scaled aspect

With the GB3D framework in place more detailed sections and data can be keyed in to stratigraphic units using a nested or child-parent approach referred to as the LithoFrame concept (Mathers *et al.*, 2011; Asch *et al.*, 2012). In modelling, the term 'resolution' is preferred to 'scale' to distinguish from outputs fixed to a scale and digital geological objects such as cross sections that can be used at a range of resolutions. Resolution is usually expressed as the mid-point of the range, it is useful to indicate that the maximum resolution data can be used at reliably.

The effective depth of modelling and definition across several resolutions is central to this concept is that the varied resolutions are consistent with each other so that collectively they form a seamless transition from the general national models to detailed or site-specific ones. As shown in Figure 11 the definition of the highest order stratigraphic units should be defined first and included in all models of a higher resolution. Here, the major stratigraphic boundaries selected at the regional 1:625 000 resolution are applied to the higher resolution models (Figure 11). On the contrary, detailed models can be generalized and incorporated into lower resolution deep regional models

Within GSI3D, the stratigraphic hierarchy is arranged in columns in the Geological Vertical Sequence (*.gvs) file that controls the project workspace. Here an example is given for the Chalk Group of the Hampshire Basin, England (Table 1) with classification indicated at six levels, each level can be

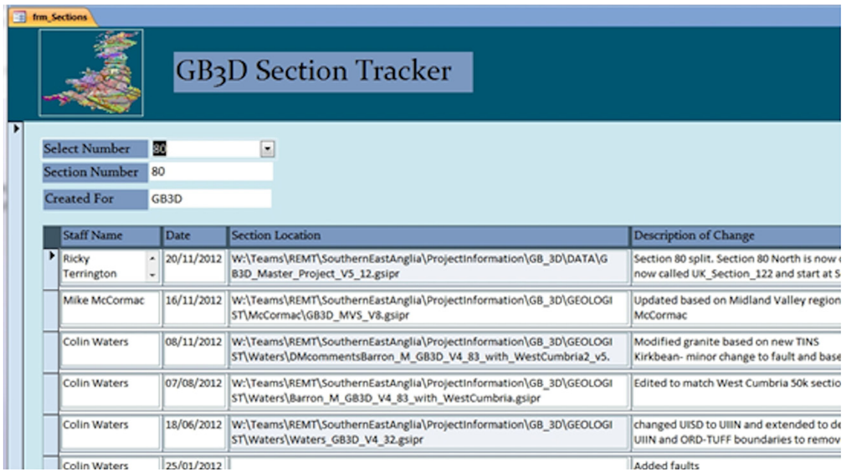

Figure 10. The GB3D section tracker.

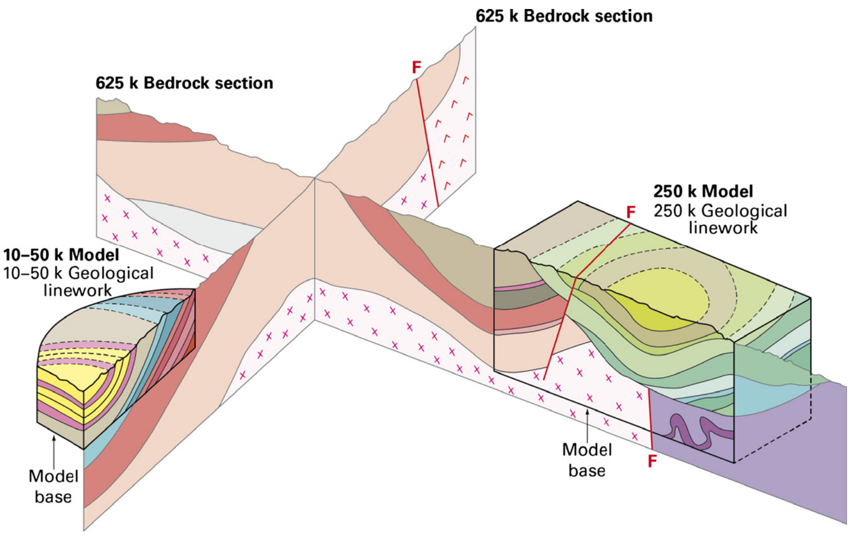

Figure 11. The LithoFrame Concept showing varied detail at differing levels of resolution.

Table 1. Example of multi-scaled stratigraphy: the Chalk Group of the Hampshire Basin.

Formation	Informal	Sub-group	Group	Sub-system	System
Portsdown chalk formation	Upper chalk	White chalk	Chalk	Upper cretaceous	Cretaceous
Newhaven chalk formation	Upper chalk	White chalk	Chalk	Upper cretaceous	Cretaceous
Seaford chalk formation	Upper chalk	White chalk	Chalk	Upper cretaceous	Cretaceous
Lewes nodular chalk formation	Upper chalk	White chalk	Chalk	Upper cretaceous	Cretaceous
Upper chalk (undifferentiated)	Upper chalk	White chalk	Chalk	Upper cretaceous	Cretaceous
New pit chalk formation	Middle chalk	White chalk	Chalk	Upper cretaceous	Cretaceous
Holywell nodular chalk formation	Middle chalk	White chalk	Chalk	Upper cretaceous	Cretaceous
Middle chalk (undifferentiated)	Middle chalk	White chalk	Chalk	Upper cretaceous	Cretaceous
White chalk subgroup (undifferentiated)	Middle chalk	White chalk	Chalk	Upper cretaceous	Cretaceous
Zigzag chalk formation	Lower chalk	Grey chalk	Chalk	Upper cretaceous	Cretaceous
West Melbury Marly Chalk formation	Lower chalk	Grey chalk	Chalk	Upper cretaceous	Cretaceous
Lower chalk (undifferentiated)	Lower chalk	Grey chalk	Chalk	Upper cretaceous	Cretaceous
Grey chalk subgroup (undifferentiated) = lower chalk	Lower chalk	Grey chalk	Chalk	Upper cretaceous	Cretaceous
Chalk group (undifferentiated) = upper cretaceous	Lower chalk	Grey chalk	Chalk	Upper cretaceous	Cretaceous

applied to the cross sections in terms of calculating the model. The base of the Grey Chalk Sub-Group in sections would also correspond to the base of the West Melbury Marly Chalk Formation wherever it is present; where absent or not identified the lowest surface defining the base of the Grey Chalk Sub-Group would then correspond to either the base of the Zigzag Chalk Formation where formation level classification has been achieved (for example where it oversteps the West Melbury Marly Chalk in Dorset) or the base of the Lower Chalk (undifferentiated).

The multi-scaled aspect, however, becomes more difficult to apply to non-stratified units such as intrusions and deformed metamorphic complexes. Techniques will be needed to enable lumping of intrusive bodies into overall plutons and aggregation of metamorphic units into complexes with a common structural style or metamorphic grade. Depiction of faults across varied resolutions remains a considerable challenge.

6. Attribution

The 341 geological units present in the GB3D_v2012 fence diagram are capable of attribution with many parameters, to date this has been done following the recent BGS 1: 625 000 scale hydrogeological dataset published by the British Geological Survey (2012). Figure 12 illustrates such attribution. Switching of attribute or colour schema of the model is instantaneous in the GSI3D software and the derivative LithoFrame Viewer which is available together with example models at: http://www.bgs.ac.uk/services/3Dgeology/lithoframeSamples.html

The various attributes are added as a column to the *.gvs file in the GSI3D project workspace (Figure 13) and corresponding colour entries are inserted in the *.gleg colour legend file. The column used to colour up the units is selected within the workspace properties or by a pull-down menu.

7. Geological rules and conventions used

As with the compilation of any geological map or model certain geological assumptions and rules are followed and conventions are defined to present the data, in the case of the GB3D_v2012 dataset these were as follows:

- Wherever possible the 1:625 000 scale map sheet linework, stratigraphy, and rock classification scheme were adopted in the section construction. In practice it was necessary to simplify some of the detail in terms of minor intrusions, minor faults, and lithological facies variations within individual units.
- Significant faults are depicted as offsets of the geology rather than as actual fault objects within the workspace.
- Superficial geology is excluded from the upgraded set of sections from 2010. This implies that where superficial deposits are present the bedrock unit now floods up to the DTM in sections. In general, the thickness of superficial deposits is insignificant at the intended section resolution.
- The depth cut-off is variable depending on the nature of geology, it is generally 1.5–3 km but lies deeper where major aquifers and potential mineral and hydrocarbon sources are present within sedimentary basins.
- A false horizontal base at an arbitrary depth has been constructed for some units to provide a base for the section, these should not be interpreted as true bases for these units.

8. Data applications and limitations

Appropriate applications for the GB3D_v2012 dataset include the following:

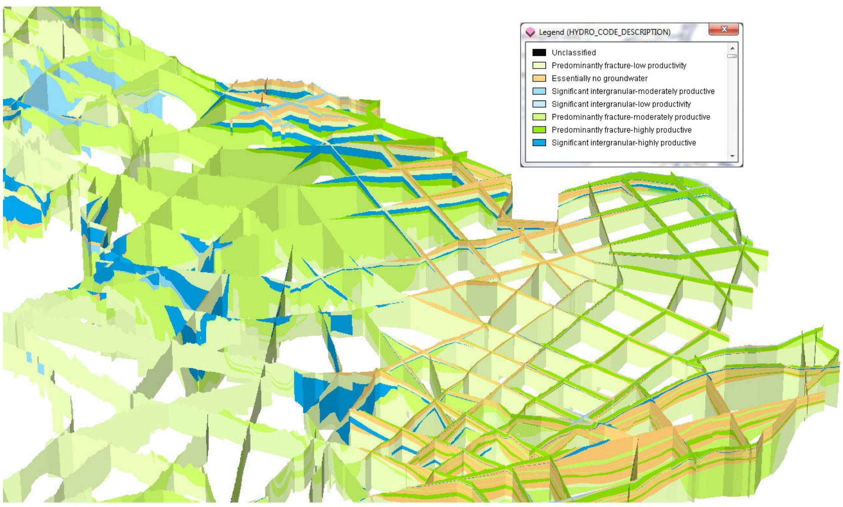

Figure 12. The fence diagram showing attribution based on aquifer classification, blue shades are significant intergranular aquifers, shades of green are fracture controlled aquifers, and brown units are non-aquifers.

	A	B	C	D	E	F	G	H
25	UCK-CHLK	120	UCK-CHLK	UPPER CHALK (UNDIFFERENTIATED)	CHALK	2A	Predominantly fracture-highly productive	Principal
26	NPCH-CHLK	125	NPCH-CHLK	NEW PIT CHALK FORMATION	CHALK	2A	Predominantly fracture-highly productive	Principal
27	HCK-CHLK	130	HCK-CHLK	HOLYWELL NODULAR CHALK FORMATION	CHALK	2A	Predominantly fracture-highly productive	Principal
28	ROWE-CHLK	135	ROWE-CHLK	ROWE CHALK FORMATION	CHALK	2A	Predominantly fracture-highly productive	Principal
29	FCK-CHLK	140	FCK-CHLK	FLAMBOROUGH CHALK FORMATION	CHALK	2A	Predominantly fracture-highly productive	Principal
30	BCK-CHLK	145	BCK-CHLK	BURNHAM CHALK FORMATION	CHALK	2A	Predominantly fracture-highly productive	Principal
31	WCK-CHLK	150	WCK-CHLK	WELTON CHALK FORMATION	CHALK	2A	Predominantly fracture-highly productive	Principal
32	WHCK-CHLK	155	WHCK-CHLK	WHITE CHALK SUBGROUP (UNDIFFERENTIATED)+	CHALK	2A	Predominantly fracture-highly productive	Principal
33	ZZCH-CHLK	160	ZZCH-CHLK	ZIGZAG CHALK FORMATION	CHALK	2A	Predominantly fracture-highly productive	Principal
34	WMCH-CHLK	165	WMCH-CHLK	WEST MELBURY MARLY CHALK FORMATION	CHALK	2A	Predominantly fracture-highly productive	Principal
35	GYCK-CHLK	170	GYCK-CHLK	GREY CHALK SUBGROUP (UNDIFFERENTIATED) = L	CHALK	2A	Predominantly fracture-highly productive	Principal
36	CK-CHLK	175	CK-CHLK	CHALK GROUP (UNDIFFERENTIATED)= UPPER CRE	CHALK	2A	Predominantly fracture-highly productive	Principal
37	PALUC-CSSM	180	PALUC-CSSM	UPPER CRETACEOUS AND PALAEOGENE ROCKS (U	CONGLOMERATE, SANDSTONE, SILTSTONE AND M	1C	Significant intergranular-low productivity	SecondaryU
38	HUCK-CHLK	185	HUCK-CHLK	HUNSTANTON FORMATION	CHALK	2A	Predominantly fracture-highly productive	Principal
39	GUGS-MDSL	190	GUGS-MDSL	GAULT FORMATION AND UPPER GREENSAND FOR	MUDSTONE, SANDSTONE AND LIMESTONE	3	Essentially no groundwater	Unproductive
40	LGS-STMD	195	LGS-STMD	LOWER GREENSAND GROUP - SANDSTONE AND M	SANDSTONE AND MUDSTONE	1A	Significant intergranular-highly productive	Principal
41	SPC-MDST	200	SPC-MDST	SPEETON CLAY FORMATION	MUDSTONE	3	Essentially no groundwater	Unproductive
42	W-LMF	205	W-LMF	WEALDEN GROUP - LIMESTONE, MUDSTONE AND	LIMESTONE, MUDSTONE AND IRONSTONE	2C	Predominantly fracture-low productivity	SecondaryU
43	W-MDSS	210	W-MDSS	WEALDEN GROUP - MUDSTONE, SILTSTONE AND S	MUDSTONE, SILTSTONE AND SANDSTONE	3	Essentially no groundwater	Unproductive
44	W-SDSL	215	W-SDSL	WEALDEN GROUP - SANDSTONE AND SILTSTONE,	SANDSTONE AND SILTSTONE, INTERBEDDED	1B	Significant intergranular-moderately productive	SecondaryA
45	SYS-SDST	220	SYS-SDST	SPILSBY FORMATION - SANDSTONE	SANDSTONE	1B	Significant intergranular-moderately productive	Principal
46	PB-LSMD	225	PB-LSMD	PURBECK GROUP - INTERBEDDED LIMESTONE ANI	INTERBEDDED LIMESTONE AND MUDSTONE	2B	Predominantly fracture-moderately productive	SecondaryU
47	LOCR-SSML	230	LOCR-SSML	LOWER CRETACEOUS UNDIFFERENTIATED	VARIED	1B	Significant intergranular-moderately productive	SecondaryA
48	PL-LMCS	235	PL-LMCS	PORTLAND GROUP - LIMESTONE AND CALCAREOU	LIMESTONE AND CALCAREOUS SANDSTONE	2B	Predominantly fracture-moderately productive	SecondaryA
49	KC-MDST	240	KC-MDST	KIMMERIDGE CLAY FORMATION	MUDSTONE	3	Essentially no groundwater	Unproductive
50	AMKC-MDST	245	AMKC-MDST	AMPTHILL CLAY FORMATION AND KIMMERIDGE C	MUDSTONE	3	Essentially no groundwater	Unproductive
51	CR-LSSM	250	CR-LSSM	CORALLIAN GROUP - LIMESTONE, SANDSTONE, SI	LIMESTONE, SANDSTONE, SILTSTONE AND MUDST	2B	Predominantly fracture-moderately productive	SecondaryA
52	WWAK-MDSS	255	WWAK-MDSS	WEST WALTON FORMATION, AMPTHILL CLAY FOR	MUDSTONE, SILTSTONE AND SANDSTONE	3	Essentially no groundwater	Unproductive
53	WWB-MDST	260	WWB-MDST	WEST WALTON FORMATION	NONE	3	Essentially no groundwater	Unproductive
54	JURU-MDSS	265	JURU-MDSS	UPPER JURASSIC ROCKS (UNDIFFERENTIATED) - M	MUDSTONE, SILTSTONE AND SANDSTONE	2C	Predominantly fracture-low productivity	NONE
55	JURU-SDSM	270	JURU-SDSM	UPPER JURASSIC ROCKS (UNDIFFERENTIATED) - S	SANDSTONE, SILTSTONE AND MUDSTONE	2C	Predominantly fracture-low productivity	SecondaryU
56	KLOX-MDSS	275	KLOX-MDSS	KELLAWAYS FORMATION AND OXFORD CLAY FOR	MUDSTONE, SILTSTONE AND SANDSTONE	3	Essentially no groundwater	SecondaryB
57	GOG-MDST	280	GOG-MDST	GREAT OOLITE GROUP - MUDSTONE	NONE	NONE	Unclassified	NONE
58	GOG-SLAR	285	GOG-SLAR	GREAT OOLITE GROUP - SANDSTONE, LIMESTONE	SANDSTONE, LIMESTONE AND ARGILLACEOUS ROC	2A	Predominantly fracture-highly productive	Principal
59	INO-LSSM	290	INO-LSSM	INFERIOR OOLITE GROUP - LIMESTONE, SANDSTO	LIMESTONE, SANDSTONE, SILTSTONE AND MUDST	2A	Predominantly fracture-highly productive	Principal
60	INO-SDLI	295	INO-SDLI	INFERIOR OOLITE GROUP - SANDSTONE, LIMESTO	SANDSTONE, LIMESTONE AND IRONSTONE	2A	Predominantly fracture-highly productive	Principal
61	IOGO-SLAR	300	IOGO-SLAR	INFERIOR OOLITE GROUP AND GREAT OOLITE GRC	LIMESTONE, SANDSTONE, SILTSTONE AND MUDST	2B	Predominantly fracture-moderately productive	Principal
62	RAG-SDSM	305	RAG-SDSM	RAVENSCAR GROUP - SANDSTONE, SILTSTONE AN	SANDSTONE, SILTSTONE AND MUDSTONE	1B	Significant intergranular-moderately productive	SecondaryA
63	JURM-MDSL	310	JURM-MDSL	MIDDLE JURASSIC ROCKS (UNDIFFERENTIATED) - I	MUDSTONE, SANDSTONE AND LIMESTONE	2C	Predominantly fracture-low productivity	NONE

Figure 13. Example gvs file, the model can be coloured or textured using any of the parameters from Column C onwards.

- General and geosciences education to illustrate of national and regional British geology (from the available download).
- Illustrating national or regional bedrock geology overviews for scientific publications for widespread and/or non specialist use e.g. Radwaste (Powell *et al.*, 2010) Shale Gas (Mathers *et al.*, 2012a) with an intended resolution of use in the 1:250 000–1:1 million range (from the available download).
- Catchment-basin-scale water management characterization yielding first-order calculated volumes based on unit coverages and cross-section extents (calculation of dataset performed in GSI3D and exported).
- Regional GIS projects including the extents (x, y) of individual geological units (generated for GIS in GSI3D).

Limitations inherent in the GB3D_v2012 dataset preclude such applications as:

- Detailed geological assessments of any kind, e.g. borehole, site or linear route prognosis.
- Resource-reserve estimation and exploration of any kind.
- Any representation or use outside the intended regional to national (1:250 000 to 1:1 million) resolution.

9. Further development of the dataset

Further work is planned for the GB3D fence diagram and is likely to include the keying in of shorter sections bridging between the existing sections to further densify the model. These sections are likely to contain higher stratigraphic resolution than the master sections and may incorporate key deep boreholes. It is also hoped to extend the depth of many sections to try and provide a more uniform depth cut-off across the model.

Further bulk attribution of the geological units will be attempted to include lithology and hydrocarbon potential. The model is also being extended offshore into the southern North Sea, and this lead will raise the perennial problem in onshore-offshore geology of a consistent stratigraphic classification, which is made difficult by the often very different types of data available to produce the interpretation. Extension to the Shetland Isles will also be undertaken in the next phase of development.

10. Data availability

The GSI3D workspace file from which the various datasets were generated for visualization and analysis (GB3D_Master_Project_V6_1_FOR_LFV.gsipr) contains the cross sections, the DTM data, and links to other supporting files including the ESRI shapefile of the published BGS 1:625 000 scale bedrock geology maps (625k_V5_BEDROCK_Geology_Polygons.shp) a geological stratigraphic sequence file (DiGMap625k_V35_0_For_LFV.gvs) and a colour legend file (DiGMap625kand50k_All_V17_0_For_LFV_GLEG) all of these with the exception of the terrain data can be viewed in the BGS LithoFrame Viewer using a calculated and encrypted GSI3D-built project workspace file (GB3D_LFV_v1_0.GSIPRe). This viewer is a free browser for visualization of models and cross sections. A good high-end graphics card, such as that used for gaming, is however essential for model visualization in this viewer. Other formats available for data visualization include 3D PDF, which can be read using Adobe Acrobat reader v6* onwards and KMZ for use in Google

Earth (preferably v7* onwards) and fly-through movie files captured in the Geovisionary software. Downloads of correlation lines for the bases of some of the younger stratified geological units in the fence diagram are also available for the GOCAD® and Petrel modelling packages.

The GB3D_v2012 dataset is served in these varied forms as free downloads from http://www.bgs.ac.uk/research/ukgeology/nationalGeologicalModel/GB3D.html and the dataset for the completed GSI3D GB3D_V2012 fence diagram with a Data Object Identifier is available at: http://www.bgs.ac.uk/services/NGDC/citedData/catalogue/f60c6923-0bd2-4469-bc7a-9c0775453ac8.html.

Acknowledgements

Many staff at the BGS have contributed to the construction of the GB3D sections in addition to the four principal authors, they are, M. Barron, P. Hopson, C. Auton, M. McCormac, P. Wilby, J. Powell, R. Crofts, K. Ambrose, D. Schofield, H. Barron and P. Strange. Attribution of units has been applied by M. Lewis and J. Bloomfield for aquifer classification. Data and workspace management has been by H. Gow, S. Thorpe, A. Myers, and I. Cooke under the guidance of R. Terrington. The customization of data and methodology for use in the GSI3D software for this task was undertaken by B. Wood and H. Kessler. At the EA we acknowledge the support of many staff over the past 4 years as this work has evolved in particular we thank Alwyn Hart, Keith Seymour, Rolf Farrell, Robert Ward and Nigel Hoad. The authors also thank the two anonymous reviewers of this paper for their helpful and constructive comments. The authors publish with the permission of the Executive Director, British Geological Survey, Natural Environment Research Council.

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