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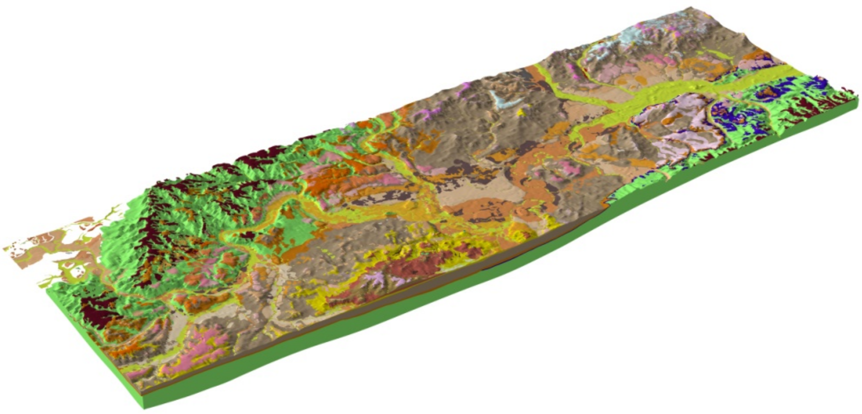
The London Basin superficial and bedrock LithoFrame 50 Model

Geology and Regional Geophysics Programme

Open Report OR/14/029



BRITISH GEOLOGICAL SURVEY

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The London Basin superficial and bedrock LithoFrame 50 Model

H. Burke, S. Mathers, J. P. Williamson, S. Thorpe, J. Ford and R. Terrington.

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Keywords

3D Geological Model, London Basin, Superficial, Bedrock.

Front cover

The model from the southwest

Frontispiece

The rockhead surface from the model

Bibliographical reference

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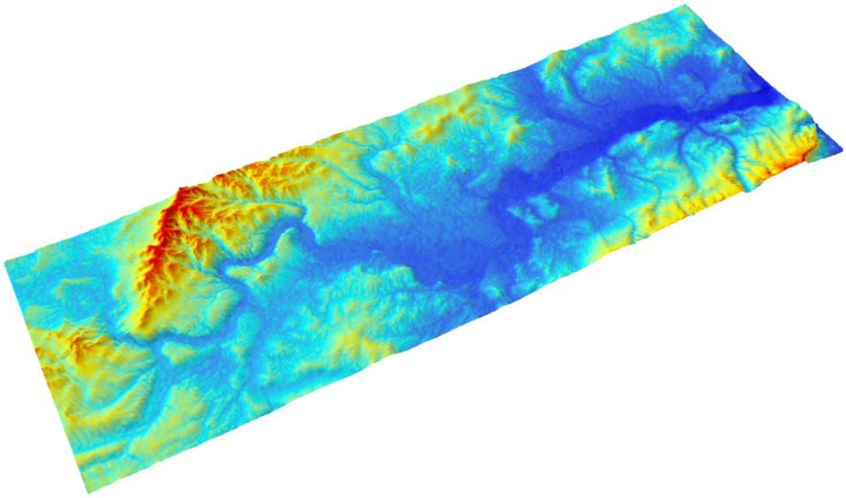

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Summary

This report describes the methodology and datasets used in the construction of the 1:50 000 resolution geological model of the London Basin.

The London Basin study area was divided into twelve 20 x 20 km tiles, with construction of the first tiles beginning in 2006 and completion of the combined model in 2014. This time period coincided with the ongoing development of GSI3D software which was used to construct much of the model. The GSI3D software was used to calculate a rockhead surface as the combined base of all the superficial units. This rockhead surface was then used as a capping surface for the modelling of the bedrock geology in the GOCAD® software.

The model complements the corresponding DiGMapGB-50 tiles and consists of 76 modelled geological units, comprising mass movement (slip), superficial, artificial and bedrock.

This report supersedes an earlier report detailing the construction of the superficial part of this model (Burke et al. 2013)

A glossary of technical terms used in this report is included at the end of this report.

1 Introduction

The London Basin 1:50 000 resolution 3D geological model covers a total area of 4 800 km^2 in southeast England (Figure 1), from easting 450 000 to 570 000 and from northing 160 000 to 200 000. Due to the large size of the modelled area, the initial construction was divided into twelve 20 x 20 km tiles (Figure 1). A separate 3D geological model was constructed for each tile using the GSI3D software and methodology (Kessler & Mathers 2004, Kessler et al. 2009). The twelve model tiles were later merged into a unified model. This report summarises the metadata compiled during the construction of the individual tiles and the development of the combined model in GSI3D and GOCAD®.

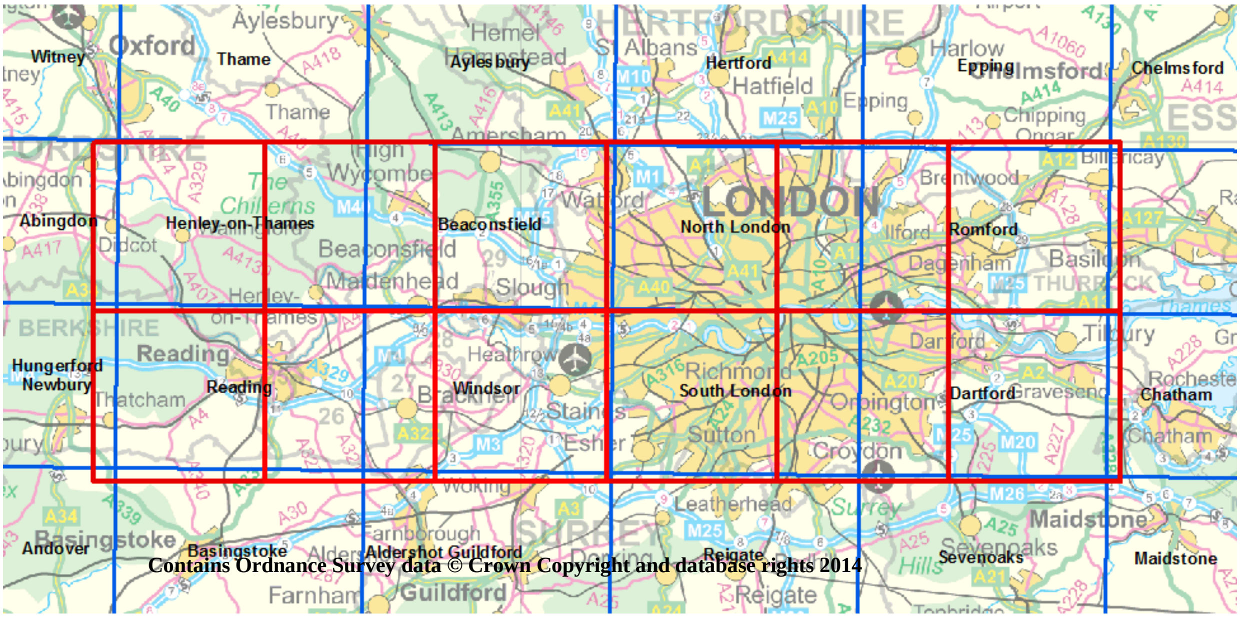

Figure 1 Location of the model and tiles 1-12

2 Model purpose and resolution

This model is intended for use at resolutions around 1:50 000, together with the corresponding DiGMapGB-50 geological map data. This model is not recommended for site specific studies or use.

Using National Capability funding work began on this model in 2006. Beginning with Areas 1 to 6, all the individual model tiles were completed by 2010. The model tiles were then amalgamated into a single GSI3D model in 2012. In total, 922 cross-sections were constructed, consulting 7174 borehole records. In all, 70 superficial and bedrock geological units have been modelled, along with landslide deposits and 5 categories of artificial ground. The bedrock units and faults that cut them were also correlated in the GSI3D cross-sections, but the corresponding stratigraphic surfaces were generated in GOCAD® as the GSI3D software is unable to calculate these faulted units. A rockhead surface derived from the combined bases of all the superficial geology units caps this bedrock model. This was generated by calculating each individual model tile with a buffer of 200m and merging them into a single rockhead surface for the entire modelled area.

A framework of cross-sections was constructed in GSI3D for each tile, with docking sections added along the grid line margins of the individual tiles. Where appropriate these were iterated between the tiles on either side to form points of commonality thus linking the geological interpretation. On completion of all twelve tiles, the calculated stratigraphic surfaces for the superficial deposits of the whole area were checked in GSI3D for artefacts resulting from the tile boundaries. Where present these were smoothed out in the production of the combined model.

In cross-section construction, discrepancies noted between boreholes and the geology indicated by the DiGMapGB-50 dataset were mainly resolved in favour of the boreholes. The model therefore updates the DiGMapGB-50 version 6 dataset. The start heights of the boreholes were retained as accurate unless they exhibited serious deviations from the digital terrain model, some were rejected as erroneous others were adjusted if required. The model is intended to complement the corresponding 1:50 000 scale geological map sheets. These map sheets are listed in the bibliography together with the accompanying memoirs/sheet explanations and the London and Thames Valley BGS Regional Guide (Sumbler, 1996).

Additional 1:50 000 scale artificial ground polygons were added to the combined model to address inconsistencies in the representation of artificial ground on different geological map sheets. Instances of artificial ground (Made, Worked, Landscaped, Disturbed and Worked & Made Ground) not already in the DiGMapGB-10 or -50 datasets were identified and captured in a 2D GIS before being added to the 3D model. These artificial deposits are indicated in the model by the 2D coverage polygons, from which 3D volumes cannot be calculated.

3 Modelled surfaces/volumes

3.1 GEOLOGICAL UNITS MODELLED

In total, 64 superficial and artificial geological units were modelled (including mass movement deposits). Table 1 lists the units in broad stratigraphic order together with the BGS stratigraphic lexicon code (see https://www.bgs.ac.uk/lexicon/) and lithology. Standard BGS map colours have been used for all superficial units (Figure 2). This should be referred to when viewing images of the model (Figure 11-13). Note that the Head and Clay-with-flints deposits are known to be polycyclic, and in the case of the latter, its formation is likely to have started as early as the Pliocene

Table 1 Stratigraphic table of geological units modelled

Inferred age	LEXICON CODE	Full name	Lithology
Holocene deposits and artificially modified ground	slip	Landslide deposits	Mass movement deposits; variable composition, dependent on the nature of the upslope material
	wgr	Worked Ground	Artificially lowered area, or void, through man-made excavation, e.g. a gravel pit
	mgr	Made Ground	Artificially raised areas, variable composition
	wmgr	Worked & Made Ground	Area of artificial cut and fill, e.g. a backfilled quarry, variable composition
	ddgr	Disturbed Ground	Area of disturbance associated with surface or near-surface collapse
	lsgr	Landscaped Ground	Extensively remodelled areas where it is difficult to delineate zones of Made, Worked or Disturbed Ground. Variable composition
	peat	Peat	Humic deposits, consisting of wet dark brown partially decomposed vegetation
	tufa	Tufa	Inorganic calcium carbonate or sinter deposited at or near springs and seepages
	alv	Alluvium	Fluvial deposits of modern flood plains, consisting of clay, silt, sand and peat

Late Anglian – Devensian glacigenic deposits and river terraces, various catchments	rtdu	River Terrace Deposits (undifferentiated)	Sand and gravel deposits directly beneath alluvium
	head	Head	Solifluction or hillwash deposit, composition dependent on source material. Usually gravelly sandy clay
	cwf	Clay-with-flints Formation	Residual deposit formed through weathering of a previous cover of Palaeogene deposits, and through dissolution of Chalk bedrock. Typically orange-brown and red-brown sandy clay with flint nodules and pebbles
	rtdo	Pleistocene River Terrace Deposits (unclassified)	Exposed river terrace deposits (not below alluvium). Composed of sand and gravel
	igd	Interglacial Deposits	Composed of silty clay
	lasi	Langley Silt Member	Varies from silt to clay, usually yellow brown and massively bedded
	shgr	Shepperton Gravel Member	Gravel with clay and sand
	no1a	Northmoor Sand and Gravel Member	Sand and gravel
	no1b		
	no		
	rosi	Roding Silt Member	Varies from silt to clay, usually yellow brown and massively bedded
	esi	Enfield Silt Member	Varies from silt to clay, usually yellow brown and massively bedded
	cfsi	Crayford Silt Member	Varies from silt to clay, usually yellow brown, often contains wind-blown sand
	kpgr	Kempton Park Gravel Member	Sand and gravel, with local lenses of silt, clay or peat
	bggr	Beenham Grange Gravel Member	Sandy clayey gravel
	sura	Summertown-Radley Sand and Gravel Member	Sand and gravel
	rtd2	2nd river terrace deposit	Sand and gravel
	ilsi	Ilford Silt Member	Sandy clay and silt
	tpgr	Taplow Gravel Member	Sand and gravel, locally with lenses of silt, clay or peat
	thgr	Thatcham Gravel Member	Sandy clayey gravel
	wv	Wolvercote Sand and Gravel Member	Sand and gravel
	rtd3	3rd river terrace	Sand and gravel
	hagr	Hackney Gravel Member	Sand and gravel, locally with lenses of silt, clay or peat
	lhgr	Lynch Hill Gravel Member	Sand and gravel, locally with lenses of silt, clay or peat
	han	Hanborough Gravel Member	Sand and gravel

	rtd4	4th river terrace deposits	Sand and gravel
	dasi	Dartford Silt Member	Varies from silt to clay, usually yellow brown, often contains wind-blown sand
	figr	Finsbury Gravel Member	Sand and gravel, locally with lenses of silt, clay or peat
	bht	Boyn Hill Gravel Member	Sand and gravel with possible lenses of silt, clay or peat
	rtd5	5th river terrace deposits	Sand and gravel
	bpgr	Black Park Gravel Member	Sand and gravel with possible lenses of silt, clay or peat
	rtd6	6th river terrace deposit	Sand and gravel
	sigr	Silchester Gravel Member	Clayey, sandy gravel

Anglian glaciation	loft	Lowestoft Formation	Till containing chalk and flint clasts
	gfdu	Glaciofluvial deposits	Sand and gravel
	gstc	Glacial silts and clays	Composed of silt and clay

Pre- and Early Anglian terraces, various catchments	wihg	Winter Hill Gravel Member	Clayey, sandy gravel
	dhgr	Dollis Hill Gravel Member	Sandy, clayey gravel, with some laminated silty beds and local silt, clay or peat lenses
	wogr	Woodford Gravel Member	Sand and gravel, locally with lenses of silt, clay, or peat and organic material
	rtd7	7th river terrace deposits	Sand and gravel
	bsgr	Beenham Stocks Gravel Member	Clayey, sandy gravel
	wlgr	Westmill Gravel Member	Gravel and sand, with local lenses of silt, clay or peat and organic material
	gcgr	Gerrards Cross Gravel Member	Gravel and sand, with local lenses of silt, clay or peat and organic material
	bygr	Bucklebury Common Gravel Member	Clayey, sandy gravel
	swgr	Satwell Gravel Member	Sand and gravel
	rtd8	8th river terrace deposit	Sand and gravel
	stgr	Stanmore Gravel Formation	Flint-dominated gravel with a clay and sandy clay matrix
	whgr	Well Hill Gravel Formation	Gravel and sandy gravel
	cwgr	Chorleywood Gravel Member	Sand and gravel
	cagr	Cold Ash Gravel Member	Sand and gravel
	bdgr	Beaconsfield Gravel Member	Sand and gravel
	suhg	Surrey Hill Gravel Member	Flint-dominated gravel

	chgr	Chelsfield Gravel Formation	Sandy flint-dominated gravel
	wggr	Westland Green Gravel Member	Sandy, clayey gravel
	sgao	Sand and gravel of uncertain age and origin	Sand and gravel

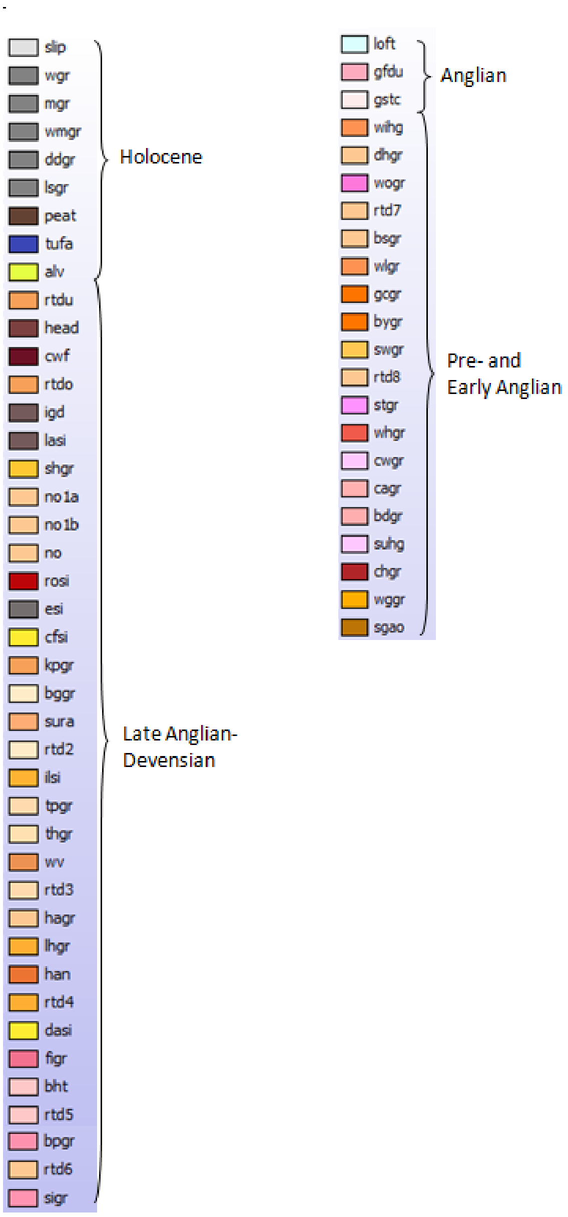

Figure 2 Superficial geological units modelled in GSI3D.

In addition 12 bedrock units (Tables 2 and 3) have been defined in the cross-sections and their distributions (envelopes or coverages) mapped in GSI3D. These data were then exported to GOCAD® for calculation of full faulted surfaces to complete the model. The list of modelled bedrock units is given at Table 2 whilst their relationships and stratigraphic hierarchy is at Table 3.

Table 2. Bedrock units modelled.

Lexicon code	Name
LNM	Lenham Formation
CMBS	Camberley Sand Formation
STHP	Stanners Hill Pebble Bed
WIDS	Windlesham Formation
SAHP	St Ann's Hill Pebble Bed
SWCL	Swinley Clay Member
BGS	Bagshot Formation
CLGB	Claygate Member
LC	London Clay Formation
HWH	Harwich Formation
LMBE	Lambeth Group
TAB	Thanet Formation

Further details of each of the superficial units are given in McMillan et al. (2011) and for all units in the systematic descriptions in the BGS lexicon of named rock units at https://www.bgs.ac.uk/lexicon/ and the geology of each district in the London Basin is covered in the respective BGS geological memoirs and sheet explanations listed in the bibliography.

Table 3 Stratigraphy of the bedrock units; those modelled are shown in bold.

<table>
<tr><th></th><th>Formation</th><th>Member</th></tr>
<tr><td rowspan="6">Bracklesham Group</td><td>Camberley Sand Formation</td><td></td></tr>
<tr><td rowspan="2">Windlesham Formation</td><td>Stanners Hill Pebble Bed</td></tr>
<tr><td>Swinley Clay Member</td></tr>
<tr><td rowspan="2">Bagshot Formation</td><td>St Ann's Hill Pebble Bed</td></tr>
<tr><td></td></tr>
<tr><td colspan="2" style="display:none"></td></tr>
<tr><td rowspan="3">Thames Group</td><td rowspan="2">London Clay Formation</td><td>Claygate Member</td></tr>
<tr><td></td></tr>
<tr><td>Harwich Formation</td><td></td></tr>
<tr><td>Lambeth Group</td><td>Reading, Woolwich and Upnor Formations</td><td></td></tr>
<tr><td></td><td>Thanet Sand Formation</td><td></td></tr>
</table>

Throughout the region the Chalk Group lies beneath the stack of modelled surfaces.

4 Model datasets used

4.1 GEOLOGICAL MAP DATA

The model covers eight 1:50 000 scale England & Wales series geological map sheets: 254 (Henley-on-Thames), 255 (Beaconsfield), 256 (North London), 257 (Romford), 268 (Reading), 269 (Windsor), 270 (South London) and 271 (Dartford); with thin small portions of a further 14 1:50 000 scale map sheets: 238 (Aylesbury), 239 (Hertford), 240 (Epping), 241 (Chelmsford), 253 (Abingdon), 258-259 (Southend and Foulness), 267 (Hungerford and Newbury), 272 (Chatham), 283 (Andover), 284 (Basingstoke), 285 (Guildford), 286 (Reigate), 287 (Sevenoaks) and 288 (Maidstone). These 1:50 000 scale map sheet areas are named and their extents are shown in blue in Figure 3, with the Area 1-12 tiles outlined in red.

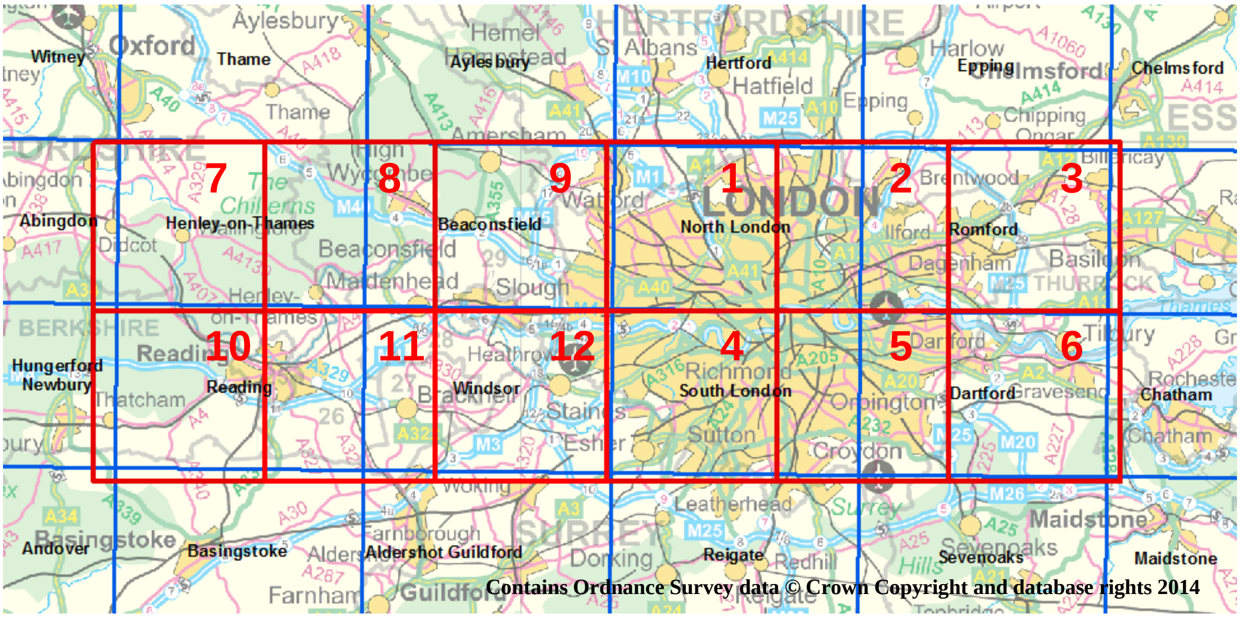

Figure 3 1:50 000 scale geological map sheets (names in black with blue extents) corresponding to the model

DiGMapGB-50 geology polygons were selected from the national DiGMapGB-50 dataset with a buffer of 1-2 km for each tile using a GIS. Polygons that are split at 1:50 000 map sheet boundaries are dissolved into single polygons in the GSI3D project. The DiGMapGB-50 extract was checked for inconsistencies, such as polygon attributes changing at map sheet boundaries, and these were rationalised where possible with precedence given to the more recent survey. The London Basin model therefore updates the geology of the DiGMapGB-50 version 6.

As the model was constructed over a number of years, several versions of DiGMapGB-50 were used. Table 2 lists the DiGMapGB-50 version initially used for each model tile.

Table 4 List of DiGMapGB-50 versions used in the model tiles

Area	DiGMap version and date	Area	DiGMap version and date	Area	DiGMap version and date	Area	DiGMap version and date
1	V3, 2006	4	V3, 2006	7	V5, 2008	10	V5, 2008
2	V3, 2006	5	V3, 2006	8	V5, 2008	11	V5, 2008
3	V3, 2006	6	V3, 2006	9	V4, 2007	12	V5, 2008

4.2 BOREHOLES

Borehole information was downloaded from the BGS Intranet Data Portal, which automatically generates GSI3D-ready files. The *.bid* file contains the location information of each borehole (easting, northing and start height) and the *.blg* file holds the downhole information recorded in the BGS Borehole Geology (BoGe) database. *Bid* and *blg* files were downloaded on a tile by tile basis, on completion of any borehole coding needed.

As the Intranet Data Portal retrieves every entry in the Borehole Geology database for a given borehole, the *.blg* file contained duplicates where the same borehole had been coded for different purposes by different interpreters. For example, a borehole coded for the production of a national Rockhead (base of Quaternary) model may have been re-coded for use in the London Basin 3D model, but both interpretations appear in the BGS borehole geology database. To address this, the *.blg* file was processed to remove multiple coding entries using a priority basis based on the Content Code (which indicates the purpose of coding) and the identity of the coder. The order of priority was revised for each model tile because different projects had carried out borehole coding in the different areas.

In addition, master *.bid* and *.blg* files were produced for the whole of the London Basin, incorporating the best available interpretation of the geology of each borehole, covering Areas 1-12. These files also include some reinterpreted borehole records coded during the recent (2013) detailed HS2 route model, which crosses Areas 1 and 9.

In total, 7174 borehole logs were considered in cross-section construction (Figure 4), comprising both confidential and open access borehole data, plus geotechnical boreholes that were absent from the BGS Single Onshore Borehole Index (SOBI). During the project assembly a GIS was used to ensure an even distribution of coded boreholes wherever possible, and additional boreholes were selected for coding from the BGS Borehole Geology database to infill the data poor areas. Selection criteria were drilled depth, borehole location and level of detail in the borehole log. Deeper boreholes were selected preferentially to constrain the deepest geological units, such as the top Chalk surface; and the borehole location was considered to ensure an even spread of borehole data across the project area. The quality of the logs themselves was also important. For example, a recently drilled borehole with a detailed log was selected preferentially over an old log conveying scant information. Old water wells were particularly difficult to use as they would often prove the depth of the top Chalk surface, but provide no information on the thickness or composition of overlying units (London Clay, superficial deposits etc.).

Boreholes were coded in the BGS Borehole Geology database using the content code ‘LS’ (London Strategic Model), which identifies coding specific to this project. To standardise the borehole coding, the superficial deposits coding scheme (Cooper et al. 2006) was used, where single letter codes represent the main lithologies (boulders are represented by the letter B, L is for cobbles, V for gravel, S for sand, C for clay, Z for silt and P for peat). For mixed compositions, the main lithology is coded first, with additional lithologies added to the right in order of decreasing proportion. An example of how the codes can be applied to increasingly mixed lithologies is shown in Table 5. In this scheme, any combination of the letter codes is permissible.

Table 5 An example of the superficial deposits coding scheme

Clay	Silty clay	Sandy, silty clay	Gravelly, sandy, silty clay	Gravelly, sandy, silty clay with cobbles	Gravelly, sandy, silty clay with cobbles and boulders
C	CZ	CZS	CZSV	CZSVL	CZSVLB

Where a Borehole Geology database entry already existed for a borehole, it was not re-coded if the level of detail was sufficient for modelling. However, where a borehole only conveyed the depth of Rockhead, it was re-coded to maximise the data available for the 3D model. A selection of borehole logs were coded in areas with a high borehole density because of the sheer number of them, and only the deepest or most detailed logs were selected for coding where clusters occurred.

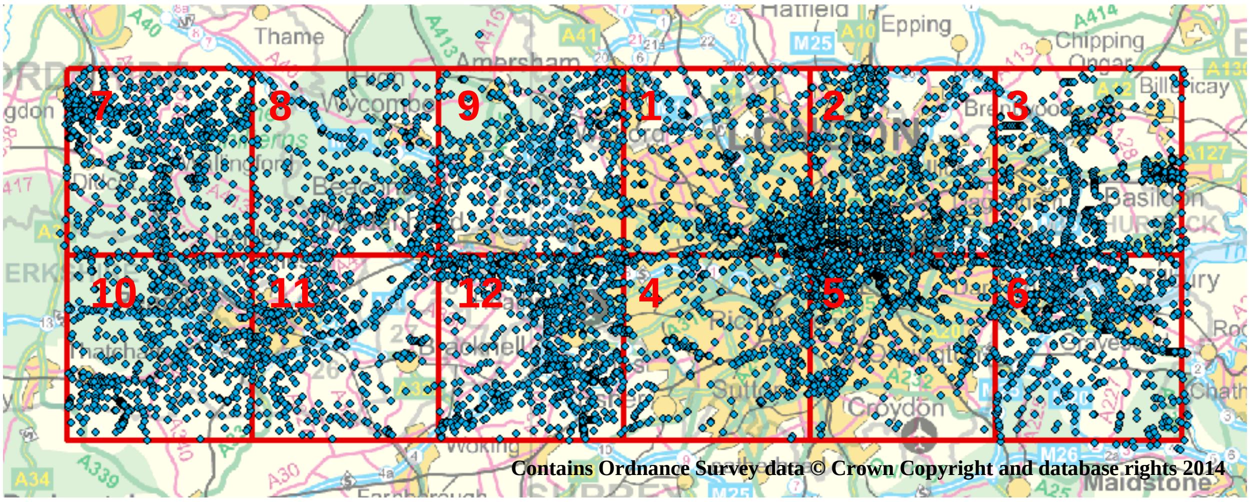

Figure 4 Location of borehole logs consulted in model construction

4.3 DIGITAL TERRAIN MODEL (DTM)

All individual model tiles used a DTM in ASCII grid format, sub-sampled from the superseded 5 m resolution CEH DTM or the later, also superseded, 5 m NextMap DTM. These DTM extracts were downloaded via the BGS Intranet Data Portal and were converted to TINs within the GSI3D project to cap each model. Areas 1-6 used a DTM with a cell size of 25 m, and areas 7-12 were constructed using a 50 m DTM.

The combined model is capped by a BGS produced Bald Earth DTM with a 100 m cell size. This DTM is based on the same NextMap DTM but with Ordnance Survey Landform Profile data inserted for extensive wooded areas as the NextMap DTM was found to be unreliable in these locations, often depicting the top of the tree canopy rather than the ground surface.

4.4 LEGACY AND OTHER 3D MODEL DATA

4.4.1 Thames Gateway models

Areas 2, 3, 5 and 6 overlap pre-existing unapproved LithoFrame 10 Thames Gateway 3D models (shown as the blue hatched area in Figure 5). In Areas 2, 3, and 5, the Thames Gateway model data was not incorporated but was improved by the London Basin model.

In Area 6, the Thames Gateway cross-sections and envelopes (unit coverages) were retained and extended to the edge of this tile, with the correlation lines reassessed, matched to the 1:50 000 scale map linework and the previously completed model tiles. The stratigraphy of these Thames Gateway cross-sections were simplified to fit the schema of the London Basin model, in particular including the removal of subdivisions within the alluvium. The earlier Thames Gateway project borehole coding was retained and decisions on whether to accept these earlier interpretations were decided on a case by case basis in the context of the revised cross-sections.

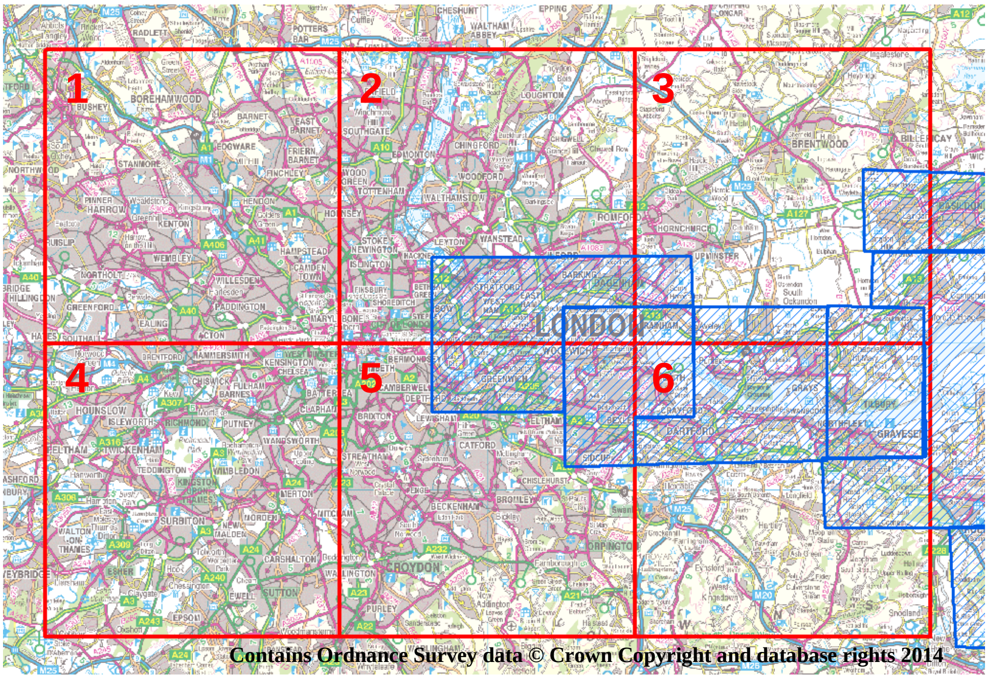

Figure 5 The Thames Gateway models, shown in blue hatching

4.4.2 HS2 route model

The 1:10 000 scale HS2 route model, commissioned by HS2 Ltd in 2013, adds more detail to the London Basin LithoFrame 50 regional model. This involved a reinterpretation of borehole data within the HS2 project area (shown in blue shading in Figure 6), which was then incorporated into the London Basin combined borehole files. Extra cross-sections were added into the HS2 area, and these were then incorporated into the London Basin regional model. The superficial deposits correlated in the London Basin model cross-sections were matched to the HS2 cross-sections. The HS2 model conveys greater detail in the anthropogenic deposits than DigMapGB-50, but this was not carried over into the revision of the London Basin model.

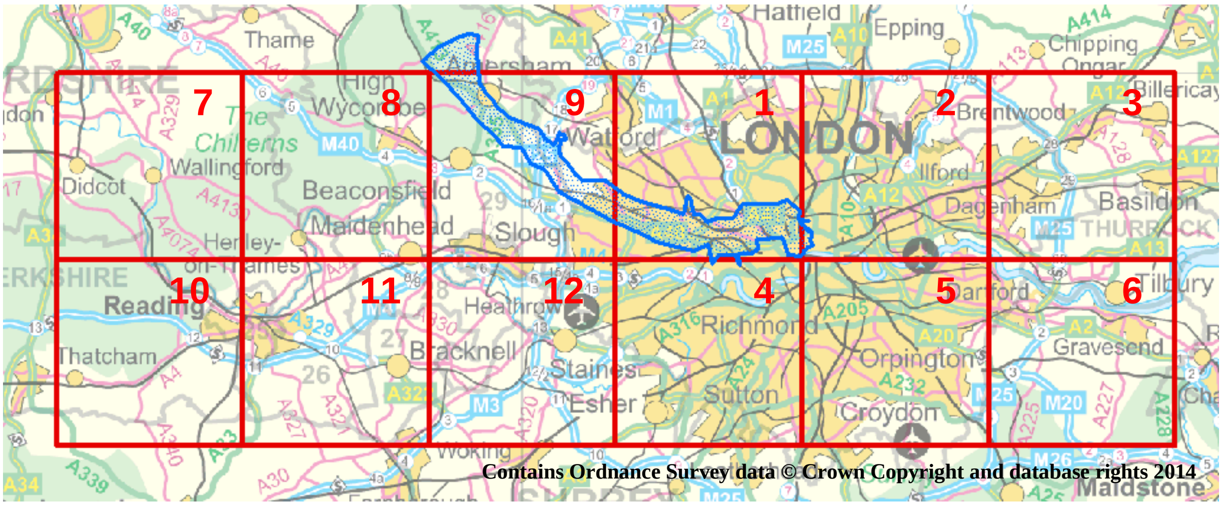

Figure 6 The LithoFrame 10 HS2 route model area, shown in blue stipple

4.4.3 Other models

In the west, the London Basin Model overlaps with bedrock models for the Berkshire Downs, the Goring Gap, and the Itchen. These do not include significant components of superficial deposits but were considered in the bedrock geology interpretation.

In the east, the London Basin Model overlaps with higher resolution models including Farringdon, Lower Lea Valley, Thames Flood Prevention, Thames Flood Defence, Tilbury Docks, and ALF

Archaeology. It also adjoins a model for Cliffe at Hoo, Kent. These models were not taken into account in the London Basin model, and in some cases (e.g. Farringdon) they post-date the basin wide model and were built using its existing cross-sections as a framework.

There are also two bedrock models referred to as the Inner London Chalk Project and Cray-Swanscombe Project that do not include superficial deposits. The former includes a subdivision of the Chalk Group, which was beyond the scope of the basin model.

The eastern half of the London Basin model coincides with the LOCUS model developed in the mid-1990s, the new model supersedes it but makes use of some of the borehole coding undertaken for this earlier study.

4.5 ARTIFICIAL GROUND REPRESENTATION

Artificial ground was already recorded on some 1:50 000 scale map sheets in the model area, but not on others. To address these inconsistencies a GIS-based desk study was carried out to identify instances of artificial ground that were not present in the DiGMapGB-50 or -10 datasets. This involved examining modern 1:10 000 scale topographic maps for areas where the ground surface has been artificially modified, for example embankments and cuttings along transport routes, or reservoirs. At the same time, the existing DiGMap artificial ground data was validated, including the resolution of mismatches across original map sheet boundaries. These were corrected in the model. However, the artificial ground categories are excluded from the model calculation because, although they are mapped as coverages in x and y dimensions, there is insufficient data to constrain the base of these deposits (z) and so produce a calculated volume. To date this updated artificial ground information has not been incorporated into the currently released version of DiGMapGB-50.

4.6 DATA COLLATION

A GSI3D project workspace was set up for each of the Area 1-12 tiles, each contained data relevant to that particular area. This included clipped national DiGMapGB-50 polygon data, a DTM with a cell size of 25 m (in Areas 1–6) or 50 m (Areas 7–12) to cap the model, and the relevant borehole data files. The boreholes, DTM and DiGMapGB-50 polygons were also buffered to include data from slightly outside the tile area in order to provide contextual information. This buffered area also provided data to help constrain the base of geological units in the absence of corresponding data near the edge of a tile.

5 Model Construction and Workflow

5.1 ALLOCATION OF MODELLING WORK

The construction of the GSI3D model was carried out on a tile-by-tile basis by the geologists listed in Table 6. A metadata diary recorded the modelling process for each individual tile, with this overall metadata summary document prepared for the combined model.

The standard GSI3D workflow described in Kessler & Mathers 2004, and Kessler, Mathers & Sobisch, 2009, was followed for constructing the cross-sections and geological unit distributions (outcrop and/or subcrop).

Table 6 Allocation of model construction work

Tile	Modeller	Start date	Completion date
Area 1	H Burke/S Mathers	2006	2008
Area 2	H Burke	2007	2008
Area 3	J Ford/H Burke	2006	2008
Area 4	S Mathers	2007	2007
Area 5	S Mathers	2007	2008
Area 6	J Ford/H Burke	2007	2008
Area 7	H Burke	2010	2011
Area 8	H Burke	2009	2011
Area 9	S Thorpe	2009	2011
Area 10	S Mathers	2009	2009
Area 11	S Mathers	2009	2009
Area 12	H Burke	2009	2010
Combined model	R Terrington	2012	2012

5.2 GSI3D CROSS-SECTION CONSTRUCTION

A framework of 922 cross-sections was constructed in the modelled area, spaced up to 3 km apart (Figure 7). This includes shallow 'helper sections', added to aid the calculation of particular units. Helper sections are especially needed along the length of alluvium and through polygons that fall between sections to provide extra depth constraint during calculation. On completion of a tile, docking sections were constructed along all the bounding grid lines. These were iterated with the adjacent model tiles as described above.

For guidance, the 1:50 000 scale geological map polygons were rendered to the DTM and displayed during section construction. However, where borehole evidence contradicted the mapped linework, precedence was given to the borehole. During borehole coding for the project, the borehole start height was entered when recorded on the log, or taken from the DTM in the absence of a start height. Thus, true borehole start heights were honoured wherever possible during cross-section construction.

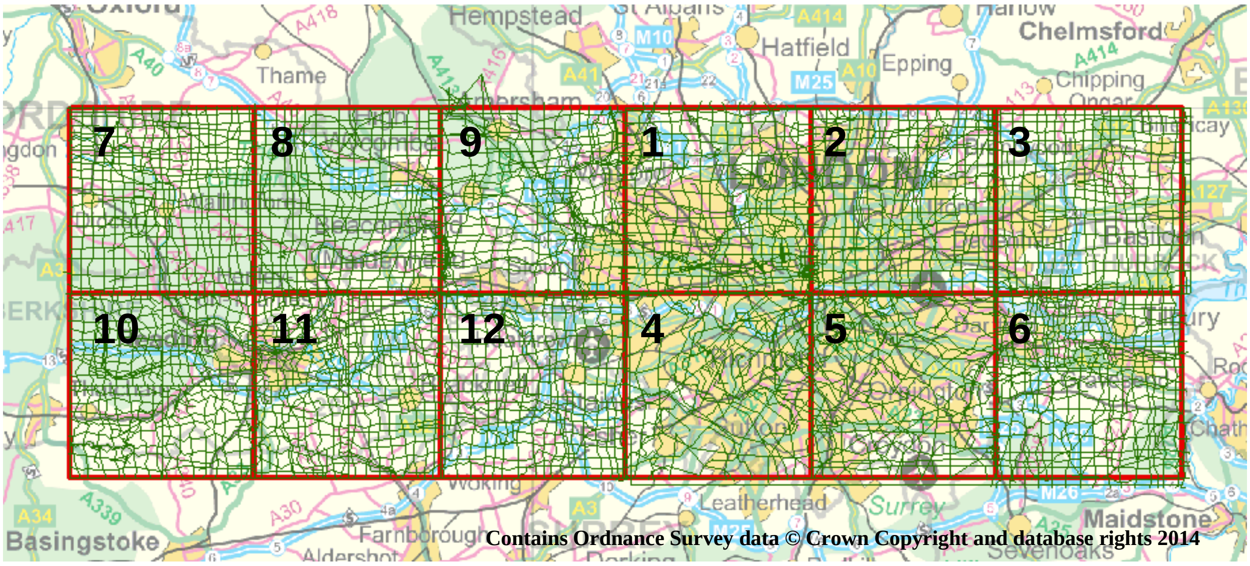

Figure 7 Framework of cross-sections used to construct the model

5.3 GEOLOGICAL UNIT ENVELOPE (COVERAGE) MAPPING IN GSI3D

When the cross-sections for a particular tile were completed, the envelopes (coverages) of each of the geological units were constructed. DiGMapGB-50 polygons were used and/or edited to delineate the outcrop extent of the geological units, and as necessary, these were combined with the subcrop portion defined by the cross-sections and boreholes.

5.4 COMBINING THE MODEL TILES

To create the combined model, all envelopes from each tile were exported as polygon shape files using the ArcGIS tools for GSI3D. A single shape file was then created for each geological unit using the ArcGIS *merge* tool on polygons with the same model code/stratigraphy (e.g. merge all 'alv' polygons). Next, the *dissolve* function was used to remove any overlaps or internal boundaries in each unit to make continuous polygons. All cross-sections from the modelled areas were then loaded into an empty GSI3D project and the newly produced coverages were imported into the corresponding geological unit.

Several checks were carried out at this stage, such as ensuring that only one version of each cross-section was loaded into the GSI3D project. Particular attention was paid to the original area boundaries, where duplicate versions of docking sections were removed if they had been loaded from more than one tile. The distribution of each geological unit was checked to ensure that real 'holes' within coverage polygons had been preserved following the GIS processing. The polygon data was also checked for inconsistencies, such as duplicates and mismatches across geological map sheets.

Once calculated, the surfaces generated for the combined model were checked for artefacts, especially along tile boundaries. These inconsistencies were addressed by improving the cross-sections in the affected area.

The 25 m DTM files used in the original model tiles were far too large for the combined model to process. To alleviate this issue a more generalised Bald Earth DTM with a 100 m cell size was deployed for the entire model area. The outcrops of superficial deposits were fitted to this dtm. Each cross-section in the model was examined and adjusted accordingly to ensure that artificial and superficial geological unit bases correspond at crossing points and to match their envelope boundaries to cross-sections. Whilst obeying the borehole data, river terraces and alluvium were re-shaped in the cross-sections and their coverages adjusted to give geologically sensible results.

A DiGMap mismatch at the north-south oriented boundary between 1:50 000 scale map sheets 255 (Beaconsfield) and 256 (North London) was also addressed in the combined model. On the western side of this boundary, the most recent edition of DiGMapGB-50 at the time of writing (version 7.22) shows Winter Hill Gravel Member on the Beaconsfield sheet and Westmill Gravel Member to the east on the North London sheet, with the dividing line running along the map sheet boundary. Taking into account the survey dates of these two geological maps, precedence was given to the Beaconsfield sheet, which was re-surveyed more recently using a desktop methods, and the entire polygon was modelled as Winter Hill Gravel Member. The correlations of the gravel deposits as shown on the BGS geological maps may be inaccurate as this linework was mapped prior to the advent of modern digital terrain models and have not used the re-interpreted linework by Gibbard (1985).

Tidal deposits were modelled in the south-east corner of Area 3 in accordance with the geological map of the Thames Estuary in Area 3 (sheet 272, Chatham). However, though tidal deposits continue south into Area 6 and westwards either side of the River Thames as far as Silvertown, they are not differentiated from alluvium elsewhere in the model. To ensure consistency across the model, tidal deposits were replaced with alluvium in Area 3 (see also Section 6 below).

The distribution of Thanet Formation was also revised in the combined model. The modelled subcrop of Thanet Formation was based on its mapped distribution and thickness in the BGS publication Geology of London (Ellison et al, 2004, Figure 9). Following a reassessment of borehole data for the HS2 3D model, the Thanet Formation subcrop was revised in the HS2 model and incorporated into the London Basin model. To ensure that the re-interpreted boundary of Thanet Formation matched the wider London Basin model, borehole data used in Areas 4 and 12 was re-examined in a GIS and the Thanet Formation boundary was adjusted accordingly.

Because of the modifications outlined above, the combined geological model supersedes all the individual model tiles.

5.5 GSI3D PROJECT MODEL FILES

A regional GVS (stratigraphic sequence file) was used for all individual model tiles and the combined model for continuity. The ‘London’ GVS was based on the pre-existing Thames Gateway GVS, but was adapted to generalise the level of detail, particularly in the alluvium. The code ‘Alv’ (the BGS Lexicon stratigraphy code for Alluvium) was used in the London GVS to define the base of all Alluvium deposits, whereas the Thames Gateway model separated the individual peat horizons and intervening silt and clay layers; these are not included in the combined model.

Progressive versions of the GVS were created when new geological units were added as they were encountered with the expansion of the modelled area. On completion of the combined model, a new GVS was created that lists only the artificial and superficial geological units in the model. Each geological unit in the GVS file is attributed with stratigraphy, lithology and age, with stratigraphy used as the primary basis for modelling.

Similarly, the London basin *.gleg* (geological colour legend) file applies to the region as a whole, and is based on the Thames Gateway file. To match the geological map sheets, the DiGMapGB-50 colours were used in the London legend file (Figure 2). A legend file specifically for the superficial model was created.

5.6 EXPORT OF BEDROCK GEOLOGY DATA TO GOCAD®

For each bedrock unit in the GSI3D model, the interpretations in the cross-sections of the base were exported en-masse as single Curve objects to a GOCAD® ASCII file (one file per unit base); these files were then loaded into GOCAD®.

Unit envelopes (coverages) were also imported into GOCAD® as Curves with a *z*-coordinate of zero metres.

The DTM was supplied as a GOCAD® surface exported from GSI3D: this was loaded into GOCAD®.

5.7 MODELLED FAULTS IN GOCAD®

The overall fault pattern is shown in Figure 8. The faults were initially digitised in GSI3D and then exported and adjusted in GOCAD® to model the bedrock units. Figures 9 and 10 show more detailed views of the modelled fault network, with individual faults labelled.

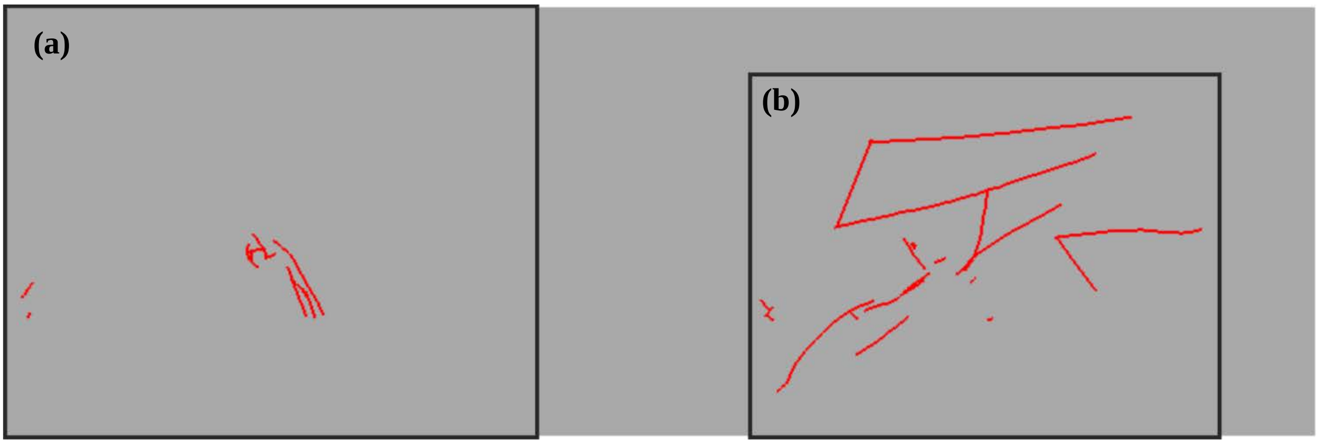

Figure 8 Overview of fault pattern, with the eastern (a) and western (b) faulted areas shown

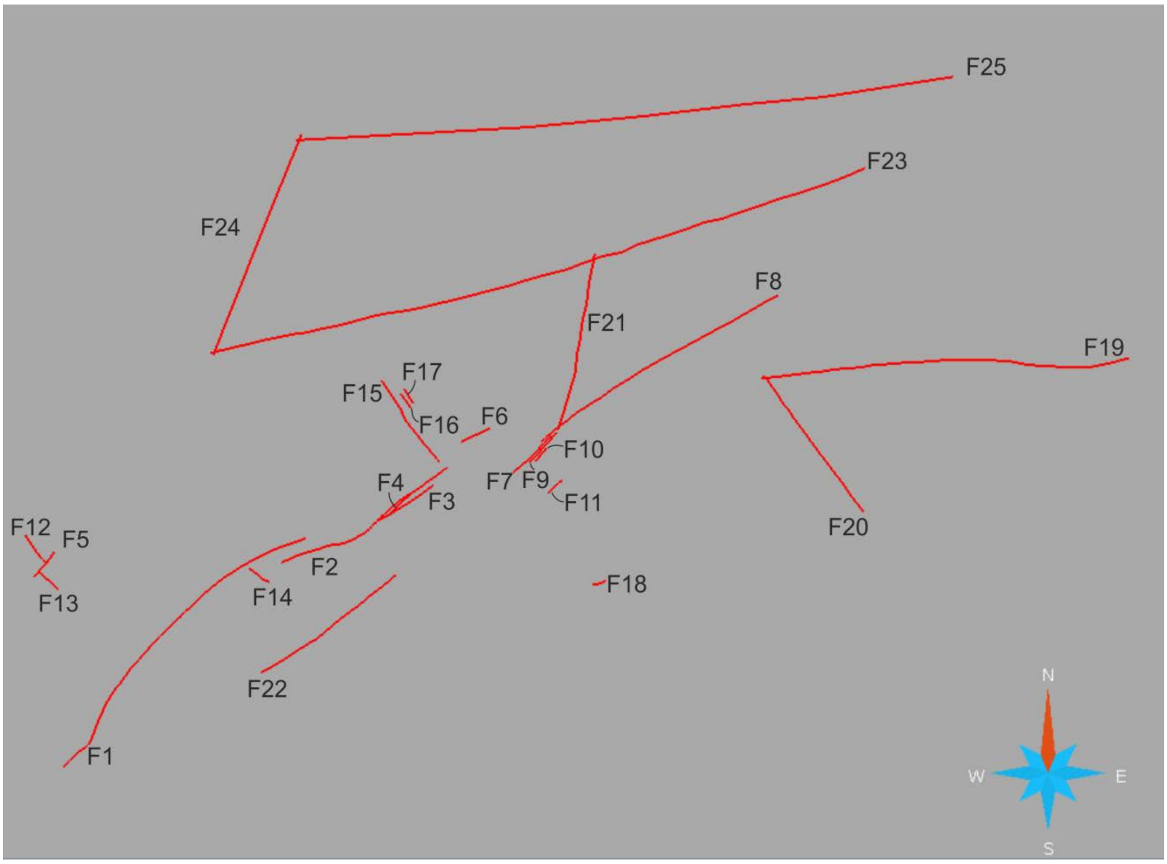

Figure 9 The eastern fault area with faults in the model labelled

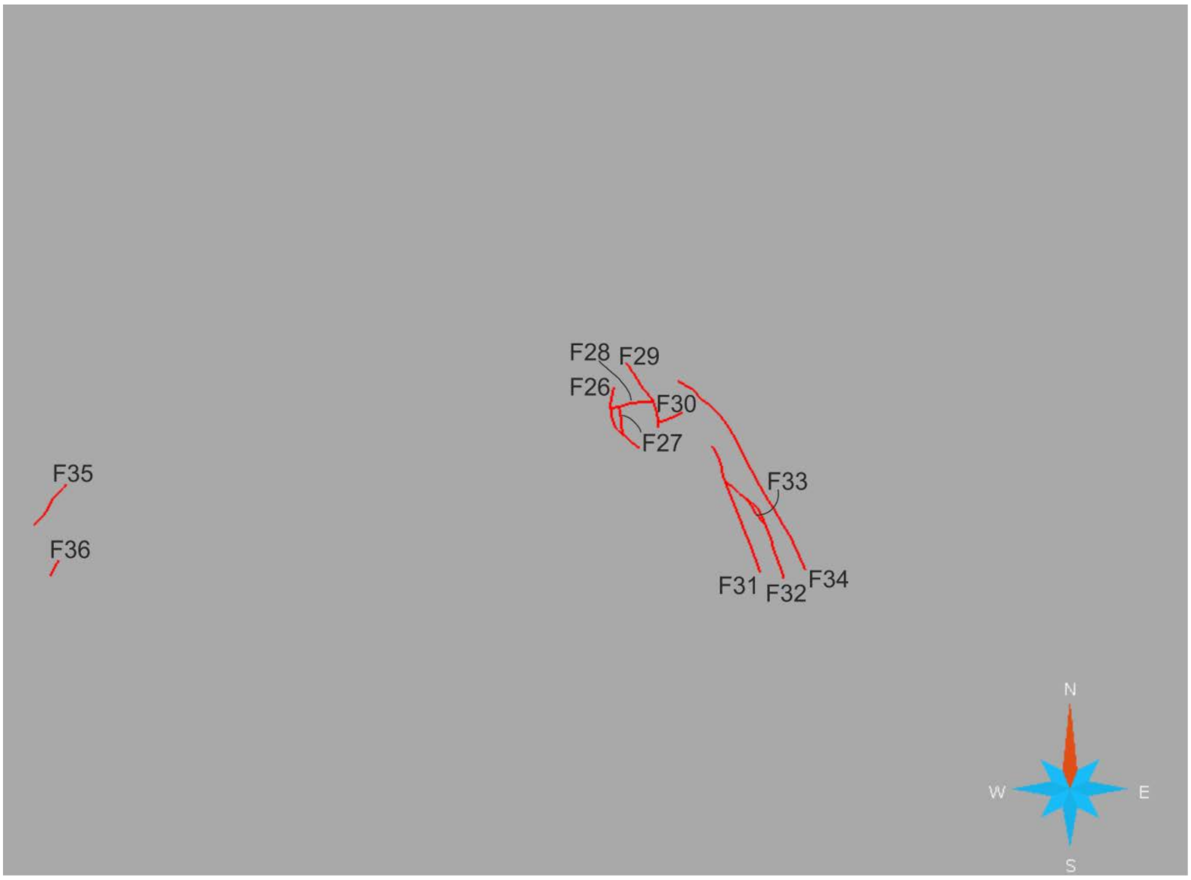

Figure 10 The western fault area with faults in the model labelled

5.8 GOCAD® MODELLING WORKFLOW

Derivation of 3D subcrop information

In order to model each surface correctly using the supplied datasets, both correlation lines along sections and the extent (subcrop) polygons must be taken into account. GSI3D can export directly the base of a geological unit across all sections, so these data are easily obtained. However, because the unit envelopes, or subcrops, are defined only as 2D map polygons, a procedure must be defined in order to assign *z*-coordinates to the subcrop data so that they can be used for 3D modelling. This process is handled automatically within GSI3D but requires a manual implementation in GOCAD®.

The general idea is that surfaces S_i, S_{i+1}, …, S_N , $i = 1, \ldots N$ are the N unit bases that comprise the model (in GSI3D these would comprise the GVS). S_0 is defined as the model capping surface and S_N is the lowest surface in the stratigraphic sequence. In other words, for all points (x, y) in the district, $S_i(x, y) > S_j(x, y)$ if $i < j$ ($i \geq 0$ and $j > 0$).

We define a set of intermediate capping surfaces C_i , $i = 1, \ldots N$, where each surface C_i is the minimum of surfaces S_0, …, S_{i-1} where they exist. By definition all points on the subcrop line of unit i lie on C_i and hence *z*-coordinates can be assigned by querying C_i at all (x, y) points on the subcrop line.

The problem is therefore to compute the set of capping surfaces; an implementation in GOCAD® is as follows:

1. On the initial model capping surface we create N new properties Z_i , $i = 1, \ldots N$, one for each unit base in the model (note that the Z property of the surface (no subscript) is the one that defines the geometry of the surface). For the London model these properties were Z01LNM,

Z02CMBS, Z03STHP, Z04WIDS, Z05SAHP, Z06SWCL, Z07BGS, Z08CLGB, Z09LC, Z10HWH, Z11LMBE, Z12TAB

2. Starting at the first unit (i=1):
3. The outline curve for the i'th unit base is projected onto the capping surface. This interpolates the Z property of the surface onto the Z property of the nodes of the outline curve.
4. The points for the unit base are assembled from the unit's correlation lines and the 3D outline curve that was defined in step 3.
5. The unit base is modelled within the geographical extents defined by its subcrop polygons.
6. The z-coordinates of the modelled surface are transferred onto property Z_i of the capping surface, where i is the number of the unit base in the sequence (i = 1, …, N).
7. Using a property script on the capping surface, we set property Z equal to Z_i (e.g. Z = Z01LNM for the first horizon)
8. Repeat for the next unit base in the succession (i=i+1) – go to step 3

Applying the above procedure to the horizon extent polygons, a set of 12 3D polygons was generated (one per unit base in the model). Each extent polygon was turned into a set of points and combined with the corresponding GSI3D unit base to give a single set of points that defines the known unit base.

Area of interest

Some unit bases have many disconnected parts, it is impractical to model each patch separately, as would normally be done. Instead, the model was constructed over the entire area of interest and then cut by the outline curves, with the unwanted parts being discarded

Modelling the unfaulted surfaces

For each unit base, a set of 3D points was obtained from the correlation lines along GSI3D sections and the 3D subcrop lines obtained as described above. Each unit base was then modelled across the entire area of interest using the GOCAD® Structural workflow.

Faults in the model

It was initially hoped that fault surfaces exported from the incomplete GSI3D London bedrock model could be used unchanged in the GOCAD® model. Unfortunately, the variable quality of fault meshes in the exported surfaces led to problems with computing the contacts between faults correctly; the decision was therefore taken to re-model the faults in GOCAD® in order to get clean fault meshes.

The remodelled faults were introduced to the Structural workflow and Fault-Fault contacts were established. After checking these, Horizon-Fault contacts were set up and the fault cuts computed. The first pass of this threw up many errors that were due to points lying on the wrong side of the fault surfaces (something that will be common in older versions of GSI3D). These were corrected by a combination of exclusion by distance from the fault surface and by manual inspection (both of these operations are in the Structural workflow).

Further tidying up

A number of artefacts were also identified with respect to the subcrop polygons, where there were occurrences of section interpretations extending outside these polygons (this is obviously physically impossible in the general case). These were again manually excluded using the tool in the Structural workflow.

6 Assumptions, geological rules and limitations

6.1 ASSUMPTIONS AND RULES

Wherever possible, the model matches the corresponding 1:50 000 scale geological map sheets. However, where mismatches occur between the interpretation of boreholes and the geological mapping, the boreholes have been used in preference. Therefore, the vast majority of the model matches DiGMapGB-50, but with minor amendments, these have not been carried over into an updated DiGMapGB-50 version at this stage.

The artificial ground layer was updated specifically for the model and has also not been incorporated into the released version of DiGMapGB-50 at present. This was carried out as a desk study using modern Ordnance Survey topographic maps and aerial photographs, with emphasis given to cuttings and embankments along major transport routes. Backfilled workings are not included, unless indicated on the relevant published geological maps.

Sub-alluvial gravel is modelled beneath river alluvium as a separate geological unit wherever it is identified in boreholes. This gravel is modelled as River Terrace Deposits Undivided (rtdu) in the majority of the model, as in most areas it is uncertain which river terrace gravel occurs beneath the alluvium. The sub-alluvial gravel is modelled as Shepperton Gravel Member (shgr), the very lowest terrace in the sequence in areas where it crops out adjacent to the modern floodplain alluvium.

Tidal River or Creek Deposits (trd) are mapped as a thin strip on each side of the River Thames and its tributaries from easting 539980 (around Silvertown) downstream to easting 568570 (Tilbury Marshes). These tidal deposits have not been differentiated from alluvium in this model, due to the close similarity in their lithologies and the gradational nature of their relationship.

6.2 MODEL LIMITATIONS

Whilst every effort has been made to ensure accuracy, with the model constructed using a framework of cross-sections according to standard GSI3D workflow and procedures, not every available borehole was used in the model. Some variation may therefore occur between the depth of units modelled and depths recorded in boreholes that do not occur in the sections.

Where mismatches in the geological linework occur at 1:50 000 scale geological sheet boundaries, precedence is given to the most recently surveyed sheet, with the older linework adjusted to the newer version. Current BGS Lexicon codes are used in the model whereas DiGMapGB-50 data uses some older nomenclature. In some areas the model is based on geological mapping before the 1930's and known to be inaccurate. These include much of the Chalk outcrop where superficial deposits are known to be much more extensive than currently shown on BGS maps.

Artificial ground, mass movement deposits (landslide deposits), tufa and head are drawn in the cross-sections, but are excluded from the final model volume calculation because the cross-sections alone provide insufficient information to calculate these units due to their complex distribution, size and shape. Much of the model was constructed from legacy data and does not include any data or re-mapping done subsequent to the time the model was constructed.

This model is intended for use at around 1:50 000 resolution, in line with the corresponding DiGMapGB-50 geological map data, and is not recommended for site specific use.

There are artefacts in the model that result from GSI3D interpretations of faults as steps in the unit base.

The throw along modelled faults is often very small and may show undue 'waviness'. The underlying reason for this is lack of data to support placing a fault at the modelled location.

The given methodology for attributing subcrop lines with z-coordinates means that the resolution of the DTM surface is propagated into the subsurface

6.3 GENERAL MODELLING LIMITATIONS

The following is a list of BGS approved generic limitations that may apply:

- Geological interpretations are made according to the prevailing understanding of the geology at the time. The quality of such interpretations may be affected by the availability of new data, by subsequent advances in geological knowledge, improved methods of interpretation, improved databases and modelling software, and better access to sampling locations. Therefore, geological modelling is an empirical approach.

- It is important to note that this 3D geological model represents an individual interpretation of the data available; other interpretations may be valid. The full complexity of the geology may not be represented by the model due to the spatial distribution of the data at the time of model construction and other limitations including those set out elsewhere in this report.

- Best endeavours (detailed quality checking procedures) are employed to minimise data entry errors but given the diversity and volume of data used, it is anticipated that occasional erroneous entries will still be present (e.g. boreholes locations, elevations etc.) Any raw data considered when building geological models may have been transcribed from analogue to digital format. Such processes are subjected to quality control to ensure reliability; however undetected errors may exist. Borehole locations are obtained from borehole records or site plans.

- Digital elevation models (DEMs) are sourced externally by BGS and are used to cap geological models. DEMs may have been processed to remove surface features including vegetation and buildings. However, some surface features or artefacts may remain, particularly those associated with hillside forests. The digital terrain model may be sub-sampled to reduce its resolution and file size; therefore, some topographical detail may be lost.

- Geological units of any formal rank may be modelled. Lithostratigraphical (sedimentary/metasedimentary) units are typically modelled at Group, Formation or Member level, but Supergroup, Subgroup or Bed may be used. Some units were only modelled at Group level because of the lack of available data across the whole region. For example the Chalk group can be modelled to formation level in some areas, but not others therefore it was decided to model at group level. Where appropriate, generic (e.g. alluvium – ALV), composite (e.g. West Walton Formation and Ampthill Clay Formation, undifferentiated – WWAC) or exceptionally informal units may also be used in the model, for example where no equivalent is shown on the surface geological map. Formal lithodemic igneous units may be named Intrusions or Dykes or may take the name of their parent (Pluton or Swarm/Centre or Cluster/Subsuite/Suite), or if mixed units Complex may be used. Highly deformed terranes may use a combined scheme with additional rank terms. Artificially Modified Ground units (e.g. Made Ground (undivided) – MGR, Landscaped Ground (undivided) – LSGR) are currently regarded as informal.

- The geological map linework in the model files may be modified during the modelling process to remove detail or modify the interpretation where new data is available. Hence, in some cases, faults or geological units that are shown in the BGS approved digital geological map data (DiGMapGB) may not appear in the geological model or vice versa. Modelled units may be coloured differently to the equivalent units in the published geological maps.

- Borehole start heights are obtained from the original records, Ordnance Survey mapping or a digital terrain model. Where borehole start heights look unreasonable, they are checked and amended if necessary in the index file. In some cases, the borehole start height may be different from the ground surface, if for example, the ground surface has been raised or lowered since the borehole was drilled, or if the borehole was not originally drilled at the ground surface.

- Borehole coding (including observations and interpretations) was captured in a corporate database before the commencement of modelling and any lithostratigraphic interpretations may have been re-interpreted in the context of other evidence during cross-section drawing and modelling, resulting in a mismatch between BGS databases and modelled interpretations

- The 3D framework model should be used to give an overall impression of the geological trends, thicknesses and geometries of the stratigraphical units but should not be used as a substitute for site investigation as the data density does not support this. In addition, the outputs of the model are subsampled from 25 m up to 50 m into grids or TIN meshes from the original calculation.

7 Model images superficial deposits

Figures 11 to 13 are 3D views of the fully calculated superficial model showing all the superficial units modelled, with key locations for spatial reference; Figure 12 shows just the post-Anglian units, and Figure 13 focuses on the pre-Anglian units. The alluvium is displayed in each figure for geographic orientation. The legend is in Figure 2.

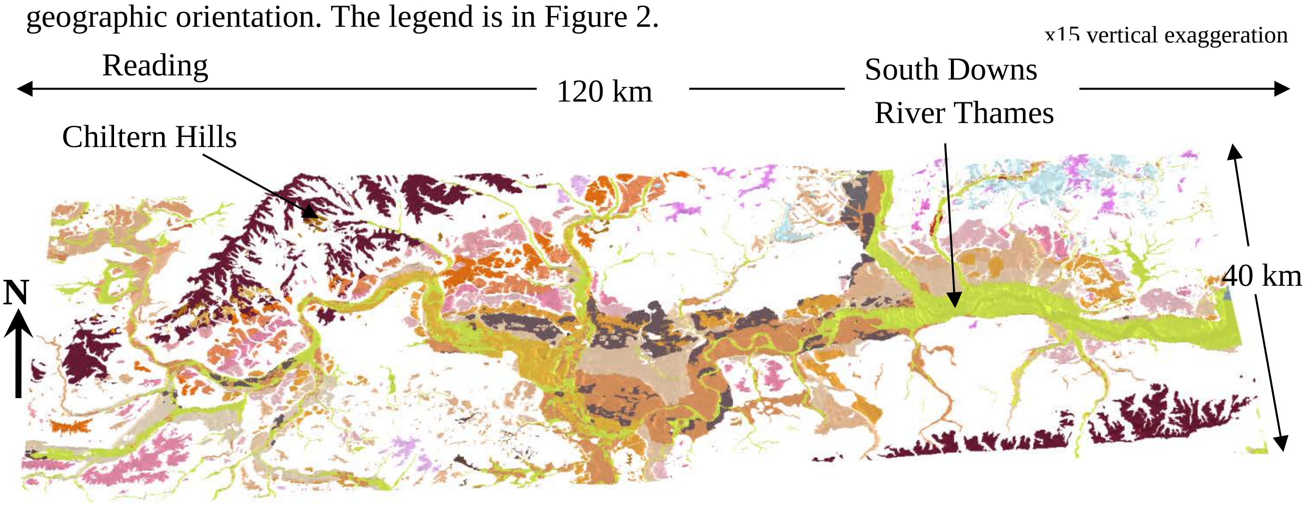

Figure 11 The superficial geology GSI3D model, looking north

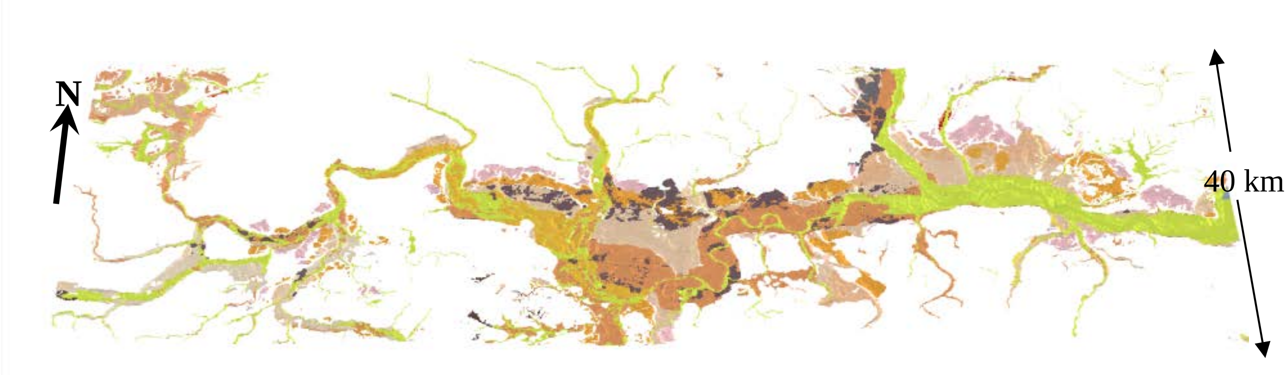

Figure 12 Late and post-Anglian river terraces and Holocene floodplain deposits

Figure 13 Anglian and pre-Anglian deposits (alluvium shown for spatial reference)

8 Rockhead elevation model

A rockhead elevation surface derived from the combined base of all modelled superficial and artificial units has an elevation range of +254.87m OD to -25.24m OD (Figures 14 and 15). This rockhead elevation surface has a cell size of 100m and caps the bedrock part of the geological model. It was generated by calculating the combined superficial model for the entire modelled area on a tile-by-tile basis, buffering each area by 200m to ensure a small overlap. The resulting rockhead surfaces were combined into a single surface for the entire modelled area. Where superficial deposits are absent, this rockhead surface corresponds to the Digital Terrain Model.

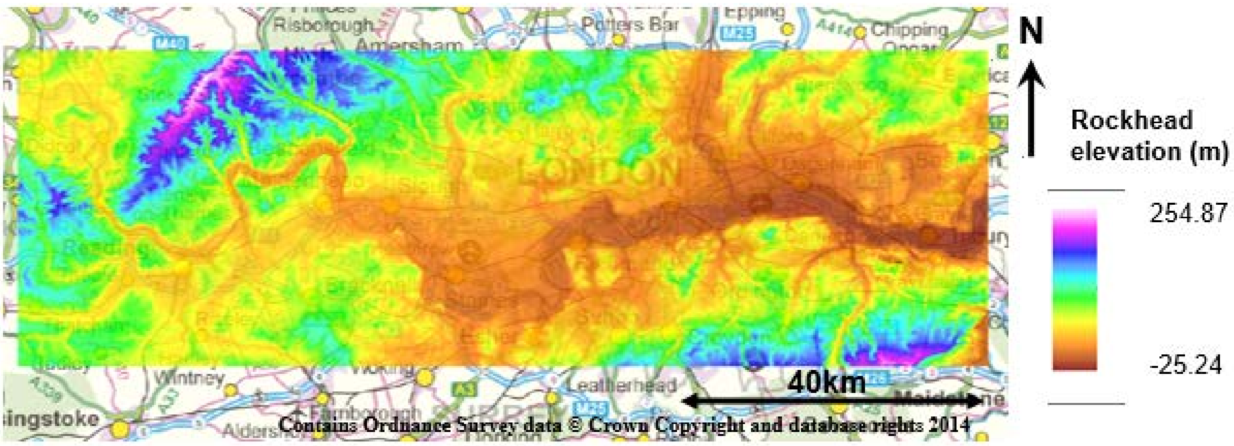

Figure 14 The rockhead elevation surface derived from the combined bases of all superficial units, artificial and landslip deposits

A 3D view of the rockhead elevation surface is displayed in Figure 14, represented as an ASCII grid with a cell size of 100m. This view shows the incision along river valleys and their broad flat floodplains.

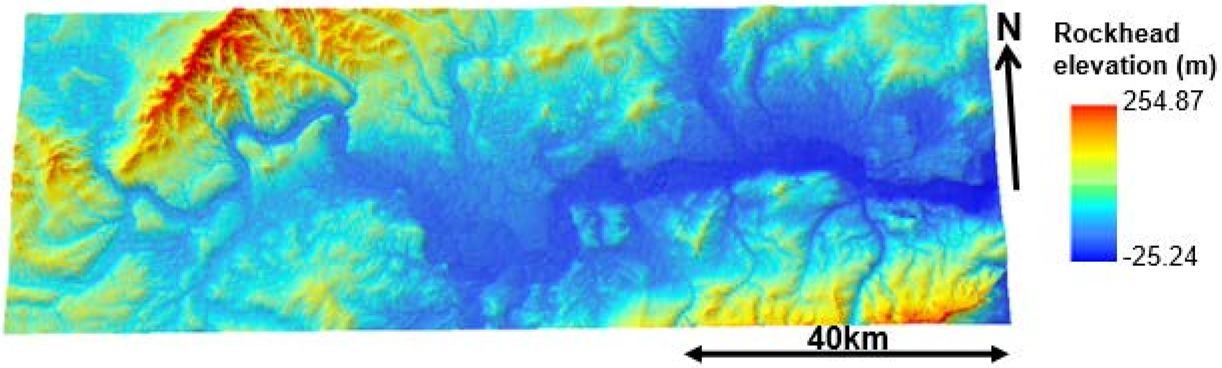

Figure 15 3D view of the calculated rockhead surface as an ASCII grid. The highest elevations are in red and the lowest in blue, vertical exaggeration is x 10.

9 Uncertainty

The model is not easy to assess in terms of uncertainty because the borehole data, reference material and geological knowledge that went into the model are difficult to represent. The borehole data used in the model is displayed in Figure 4. However, whilst showing the distribution and density of boreholes, this does not convey the depth of the borehole, the quality of the log itself or the reliability of the borehole coding.

10 Model QA

In order for a geological model to be approved for publication or delivery to a client a series of QA checks is carried out. This includes visual examination of the modelled cross-sections to ensure that they match each other at cross-section intersections and fit the borehole and geological map data used. The model calculation is checked to ensure that all units calculate to their full extent within the area of interest and the modelled geological surfaces are checked for artefacts such as spikes and thickness anomalies. The naming convention of the modelled geological units is checked to ensure that recognised entries in the BGS Lexicon of Named Rock Units (http://www.bgs.ac.uk/lexicon/home.html) and the BGS Rock Classification Scheme (http://www.bgs.ac.uk/bgsrcs/) are used as far as possible. Geological models are accompanied by a standard metadata report, such as the London Basin superficial and bedrock Lithoframe 50 model metadata report (Burke et al., 2014), which describes the datasets used in the model and records any geological decisions made during the model construction process.

Any issues found in the QA checking process are recorded and addressed before delivery/publication of the model.

11 Model images bedrock deposits

Not in a metadata specification but can be very useful for numerous subsequent purposes – key labelled images of the model and fault model.

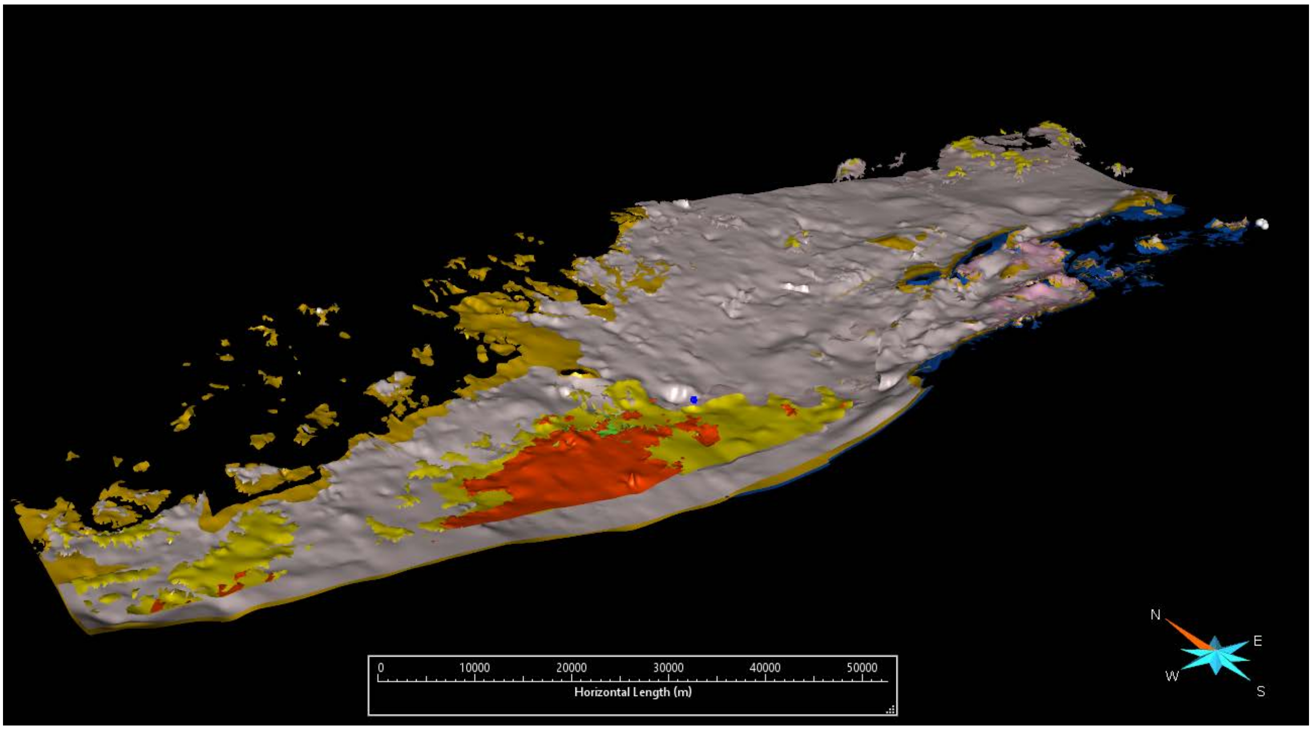

Figure 16 London Lithoframe 50 Bedrock model (looking from South-West to North-East) – x20 vertical exaggeration

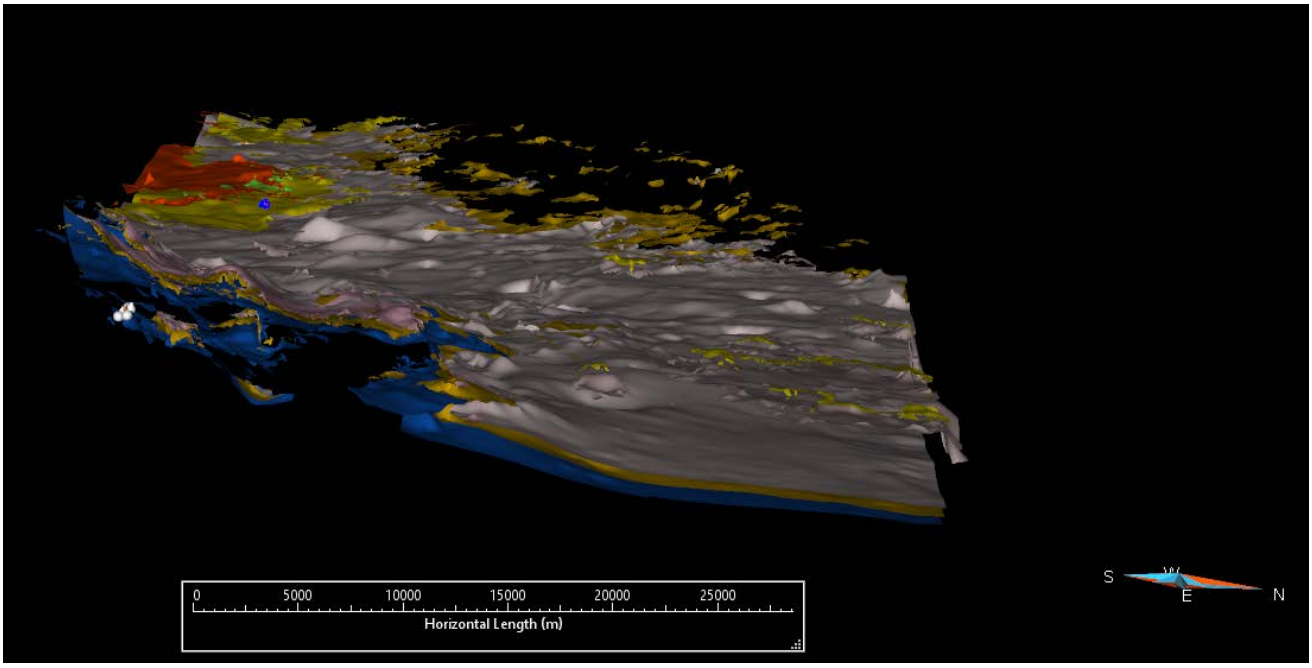

Figure 17 London Lithoframe Bedrock model (looking from East to West) – x20 vertical exaggeration

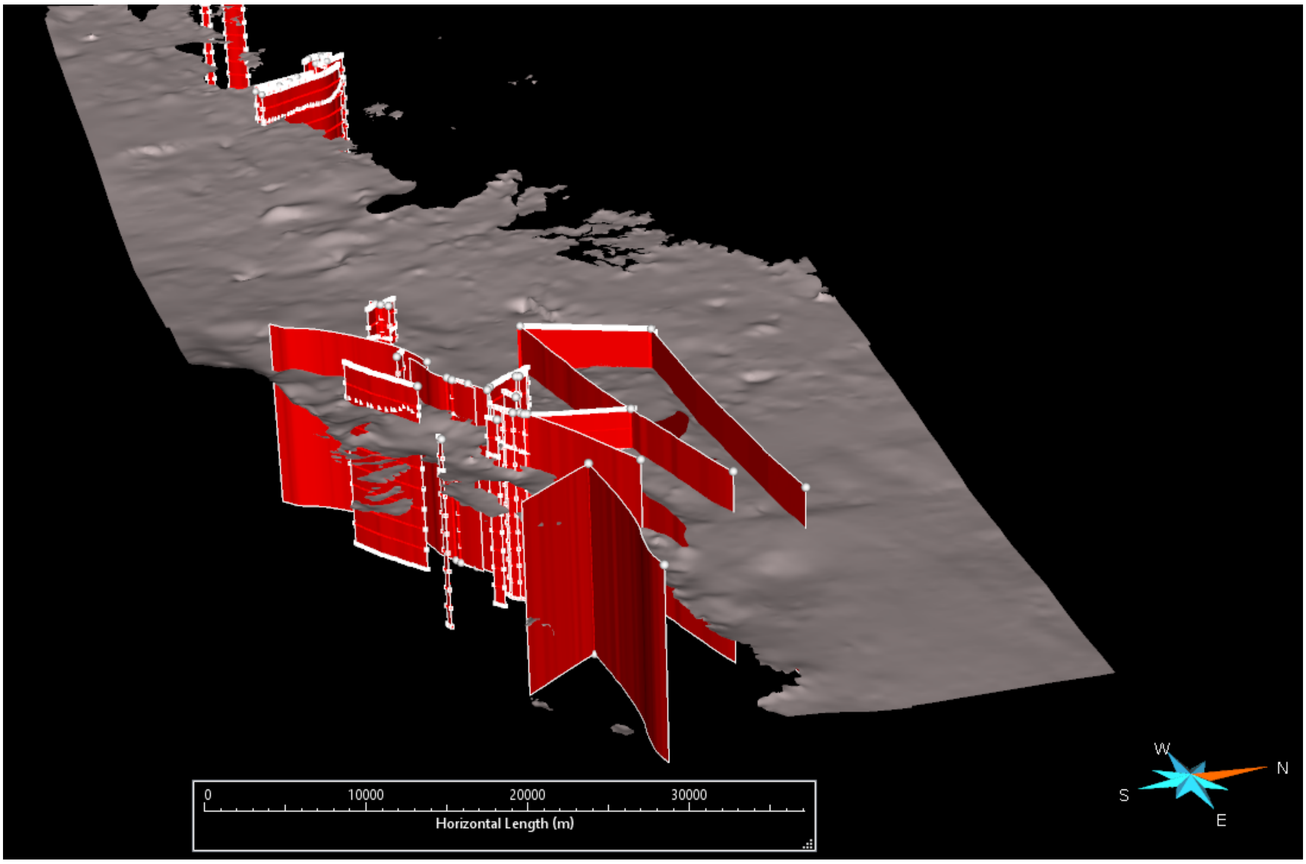

Figure 18 Fault surfaces against the base of London Clay surface

Glossary

BGS Lexicon	The Lexicon of Named Rock Units is a list of geological units that appear on all BGS geological maps, with details on their lithologies. This is accessible via the BGS website at: http://www.bgs.ac.uk/Lexicon
Bid file	GSI3D borehole identity file derived from the SOBI database (see below), which stores the locations of boreholes as eastings, northings and start heights
Blg file	GSI3D borehole log file, which stores the interpretation downloaded from the Borehole Geology database
BoGe	BGS Borehole Geology database for the standardised entry of data recorded on borehole logs
DiGMapGB-50	Digital 1:50 000 geological map data
DTM	Digital Terrain Model – a model of surface of the solid Earth (generally the boundary between geosphere and atmosphere or hydrosphere). This is traditionally derived from OS contours and spot heights and should therefore exclude all buildings, trees, hedges, crops, animals etc. Sometimes also referred to as a 'bald earth' model
Envelope	Defined here as the extent, or coverage, of a geological unit in plan view, forming a 2D distribution map of the particular unit, or presence/absence map
Fence Diagram	The completed framework of cross-sections
GDI	Geoscience Data Index, an ArcGIS platform for displaying BGS data, including boreholes, with links to scans, and geological map polygons
Georeferenced	ArcGIS process where a scanned image is registered to British National Grid
GOCAD®	3d geological modelling package utilised mainly for bedrock modelling. GOCAD® Consortium web site: http://www.gocad.org/w4/index.php/consortium/consortium
GSI3D	Geological Surveying and Investigation in 3D, a geoscience modelling software package. GSI3D Research Consortium web site: http://www.gsi3d.org.uk
SOBI	Single Onshore Borehole Index, a database where location details of borehole logs are stored, giving positional information in x, y and z with respect to British National Grid
TIN	Triangular Irregular Network – a digital elevation surface with triangle-shaped cells, rather than grid squares

Bibliography

The British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

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England and Wales sheet 240 Epping, Solid and Drift edition. Original survey at one inch scale published in 1868-1884. Resurveyed at 1:10,560 scale by R A Ellison, D Millward, M J Heath and C R Bristow in 1969-1970 and 1975-1977.

England and Wales Sheet 241 Chelmsford. original one inch survey published in 1868 (solid), drift surveyed in 1871. re-surveyed at six inch scale by r c bristow and r d lake in 1966-70, published 1975.

England and Wales Sheet 255 Beaconsfield. Original survey at 1:61,360 scale in 1861, drift added in 1871. Resurveyed at 1:10,560 scale and published in 1922. substantially resurveyed at 1:10 000 scale by A N Morigi, R T Mogridge, R J Marks and I T Williamson in 2002 and P J Strange in 1992.

England and Wales sheet 256 North London. Original survey at 1:63:360 scale published in 1861-1868 with superficial deposits added in 1871-1876. Surveyed at 1:10,560 scale in 1889-1922 with minor amendments in 1949. Partial resurvey by R A Ellison in 1977 and F G Berry in 1979-1982. Reconstituted at 1:10 000 scale with Amendments by P J strange and S J Booth in 1991-1992.

England and Wales sheet 257 Romford. Original survey at 1:63,360 scale published in 1868, with drift added in 1871-1876.resurveyed at 1:10,560 scale in 1902 with partial resurvey in 1922-1923. Minor amendments in 1941 and 1966-68. Resurveyed at 1:10 000 scale by A Smith, B S P Moorlock, P J Strange, R A Ellison, A J M Barron, M McKeown, R D Lake, F G Berry, D Millward and R Bristow in 1970-1994.

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England and Wales new series one inch map sheet 269 windsor, drift edition. partially re-surveyed in 1910-11 by h dewey and c n bromehead, published in 1922.

England and Wales Sheet 270 South London. original survey at one inch scale published in 1861-1868, drift added in 1869-1889. resurveyed at six inch scale in 1898-1914, published in 1921. partly resurveyed and revised by f g berry, t e lawson and b s p moorlock in 1973-1980. resurveyed and revised at 1:10 000 scale by p j strange, d h jeffrey, a j m barron, i t williamson, r a ellison, a smith, r t mogridge and s j booth in 1992-95. published in 1998.

England and Wales sheet 271 Dartford. Original survey at one inch scale published in 1864 and 1868 with Drift added in 1864 and 1889. Resurveyed at six inch scale by T I Pocock in 1902, H G Dines in 1921, H Dewey and C E Bromehead in 1913, 1914, 2920 and 1921. minor amendments in 1951 and 1966-70.

England and Wales Sheet 272 Chatham. Original survey at one inch scale published in 1864-1868 with revisions in 1871-1889. Partial resurvey at six inch scale by C E N Bromehead in 1920-21, remainder resurveyed by S Buchan, H G Dines, S C A Holmes and A J Robbie in 1937-1938.

England and Wales Sheet 285 Guildford. Original survey at 1:63,360 published as solid edition in 1862 and 1868, drift edition published in 1887. Surveyed at 1:10,560 scale in 1894-1898. Partially resurveyed in 1981-1982, revised at 1:10 000 scale by I T Williamson, R A Ellison and E R Shephard-Thorn in 1981-1982.

England and Wales Sheet 286 Reigate. Original survey at six inch scale published in 1864, 1862 and 1863 with drift additions in 1886, 1889 and 1887. Partially resurveyed at six inch scale by H Dewey in 1911, remainder resurveyed by H G Dines and F H Edmunds in 1928-1930.

England and Wales Sheet 287, Sevenoaks. Original survey at six inch scale published in 1864 with drift added on 1886, partly revised in 1889. Partial resurvey at six inch scale by H Dewey in 1913-14 and C N Bromehead in 1921. Remainder resurveyed by S Buchan, H G Dines, F B A Welch and S C A Holmes in 1930-36. Partial resurvey by C R Bristow in 1965.

England and Wales Sheet 288 Maidstone. Original survey at one inch scale published in 1868 and 1864 with drift added in 1875 and 1886. Resurveyed at six inch scale in 1946-1950 by F H Edmunds, J Ineson, D A Gray, J G O Smart and B C Worssam.