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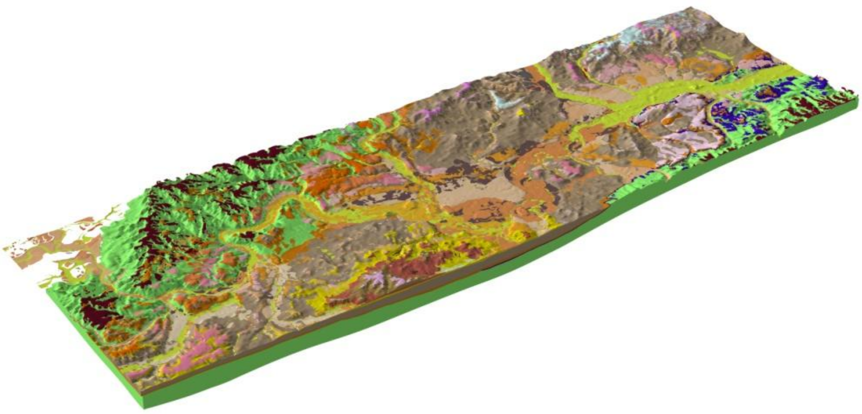
The London Basin superficial and bedrock LithoFrame 50 Model

Geology and Regional Geophysics Programme

Open Report OR/14/029



BRITISH GEOLOGICAL SURVEY

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

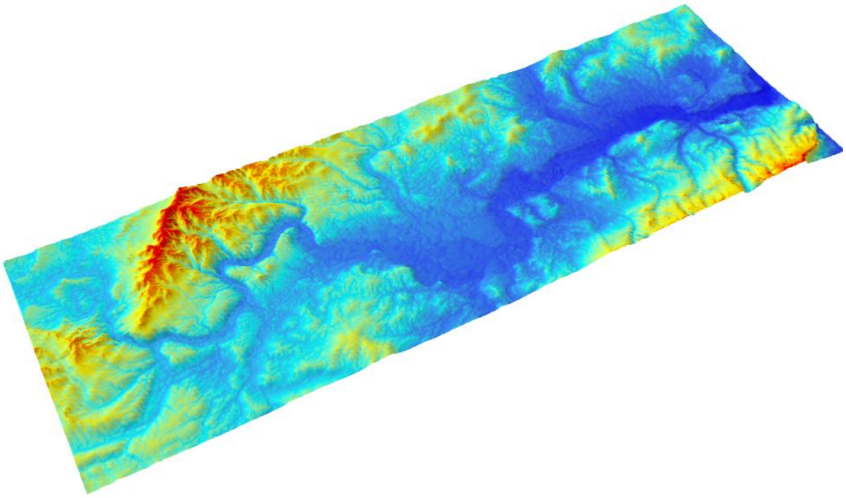
Keywords

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

Front cover

The model from the southwest

Frontispiece



The rockhead surface from the model

Bibliographical reference

H. BURKE, S. J. MATHERS, J. P.WILLIAMSON, S. THORPE, J.FORD AND R.L. TERRINGTON. 2014.
The London Basin superficial and bedrock LithoFrame 50 Model . *British Geological Survey Open Report*, OR/14/029. 27pp.

Keyworth, Nottingham British Geological Survey 2014

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Contents

Summary

This report describes the methodology and datasets used in the construction of the 1:50 000 resolution superficial and bedrock 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 (base Quaternary and Anthropocene) surface that 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 of the area and consists of about 80 modelled geological units, comprising mass movement (landslip), artificial, superficial, 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 is included at the end of this report.

1 Introduction

The London Basin 1:50 000 resolution geological model covers a total area of 4 800 km^2 in southeast England (Figure 1), stretching from easting 450 000 to 570 000 and from northing 160 000 to 200 000. Because of 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 and subsequent modelling and calculation of the bedrock units was completed in GOCAD®. This report summarises the metadata compiled during the construction of the individual tiles and the development of the combined model.

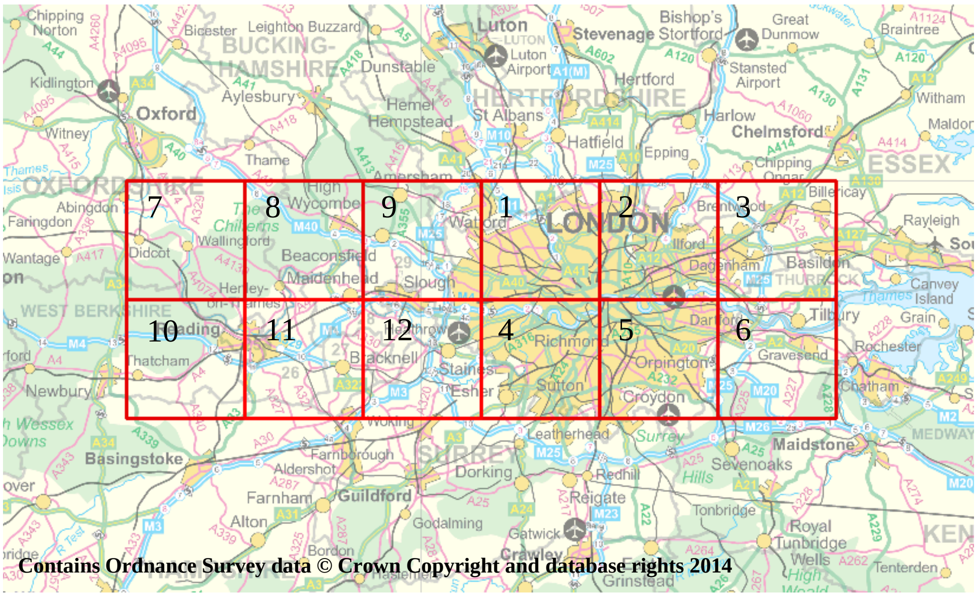

Figure 1 Location of the London Basin model and component tiles.

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 any site specific studies or more detailed uses.

Work began on this model in 2006, starting with tiles 1 to 6, all the individual 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, 74 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 down to the base of the Palaeogene, but the corresponding stratigraphic surfaces were generated in GOCAD® as the GSI3D software is unable to calculate these faulted units. Four further deeper low-resolution bedrock geological units (Cretaceous and Jurassic) derived from a larger regional model were added to this model to ensure complete coverage to a minimum depth of several hundred metres, although the depth of the model is variable across the area due to the distribution of the geological units modelled.

The initial framework of cross-sections was constructed in GSI3D for each model tile, with docking sections added along the grid line boundaries 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 across the whole area. On completion of all twelve tiles, the calculated stratigraphic surfaces for the superficial deposits for the whole area were checked for discrepancies occurring at the tile boundaries. Where present these were smoothed out in the combined model.

In cross-section construction, discrepancies noted between boreholes and the geology indicated by the DiGMap 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 as required. The model is intended to complement the corresponding 1:50 000 scale geological map sheets albeit with minor enhancements. 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 map polygons were added to the combined model to address inconsistencies and omissions in the representation of artificial ground on the different 1: 50 000 scale geological map sheets. These instances of artificial ground (Made, Worked, Landscaped, Disturbed and Worked & Made Ground) identified and captured in a 2D GIS before being added to the 3D model. These artificial deposits remain indicated in the model only by their 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 for each (see https://www.bgs.ac.uk/lexicon/) and lithology. Standard BGS map colours have been used for all superficial units in the model (Figure 2). These should be referred to when viewing images of the model in this report. 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 artificial and superficial 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

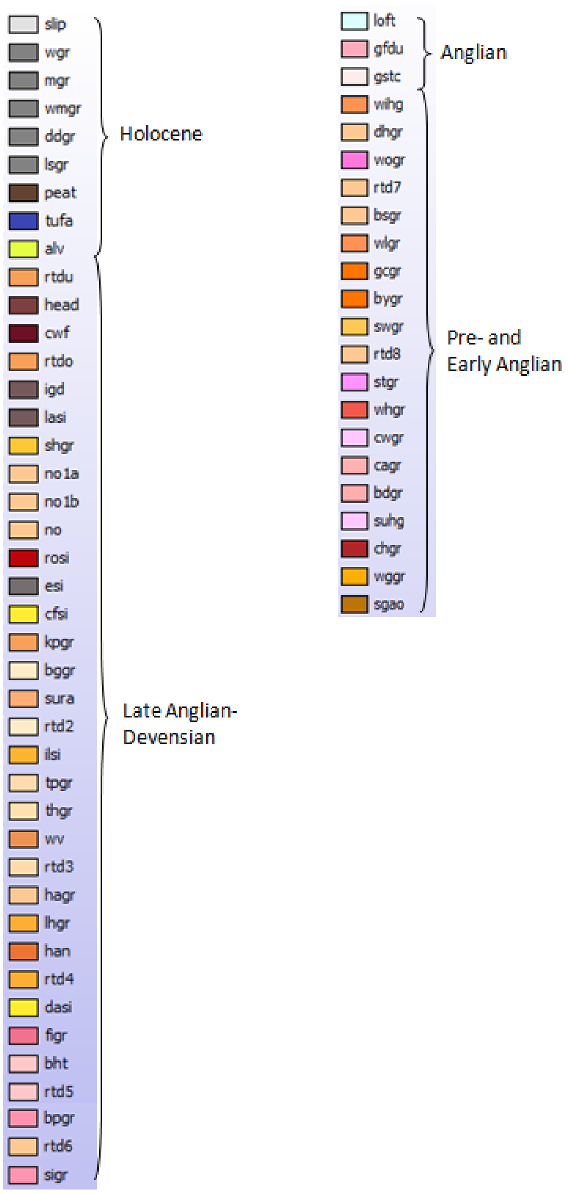

Figure 2 Superficial geological units modelled in GSI3D.

In addition 12 bedrock units (Tables 2 and 3) were included in the cross-sections and their distributions (envelopes or coverages) modelled in GSI3D, some of these units are faulted and the faults were also defined in the cross-sections. These data were then exported to GOCAD® for calculation of full faulted surfaces to complete the bedrock part of 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 in GSI3D-GOCAD.

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

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

	Formation	**Member**
Bracklesham Group	**Camberley Sand Formation**	
	Windlesham Formation	**Stanners Hill Pebble Bed**
		Swinley Clay Member
	Bagshot Formation	**St Ann's Hill Pebble Bed**
Thames Group	**London Clay Formation**	**Claygate Member**
	Harwich Formation	
Lambeth Group	Reading, Woolwich and Upnor Formations	
	Thanet Sand 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.

Finally deeper surfaces defining four further geological units were added to the base of the model to complete coverage to a depth of several hundred metres throughout. The base of the model does vary across the area rather than being terminated by a specified depth. These surfaces were imported from a lower resolution model of the whole London Basin developed in GOCAD® (Terrington et al. 2011). The surfaces comprise the base of the Chalk Group, the Gault and Upper Greensand combined, the Lower Greensand and undivided Jurassic strata.

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); together 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.

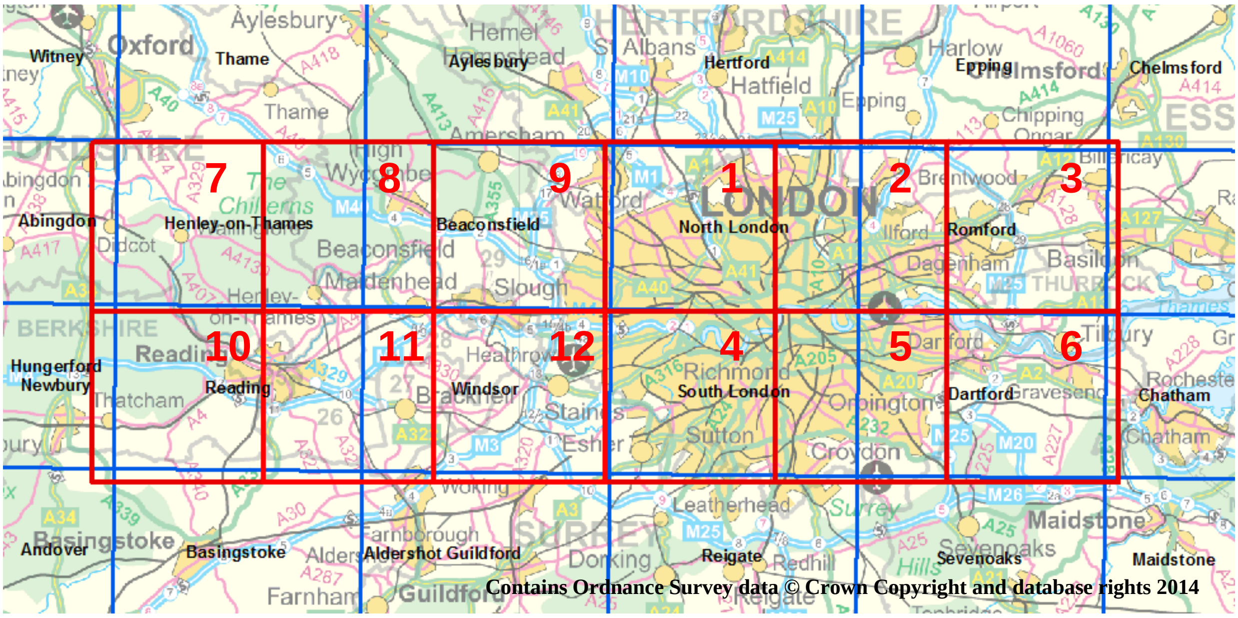

Figure 3 1: 50 000 scale geological map sheets corresponding to the model

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 were dissolved into single polygons in the combined GSI3D project. The DiGMapGB-50 extract was checked for inconsistencies, such as polygon attributes changing at the map sheet boundaries, and these were rationalised where possible with precedence given to the more recent survey and nomenclature. The London Basin model therefore updates the geology of the DiGMapGB-50 version 6.

Because 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	V 3, 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 model 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. On completion of any borehole coding needed the bid and blg files were downloaded on a tile by tile basis.

As the Intranet Data Portal retrieves every entry in the Borehole Geology database for a given borehole, the blg file contained duplicates where a 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 on a priority basis, using 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. These files also include some the reinterpreted borehole records coded during in the recent (2013) detailed HS2 route model, which crosses tiles 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. 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 often prove the depth of the top Chalk surface, but provide no information on the thickness or composition of overlying units.

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, almost 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.

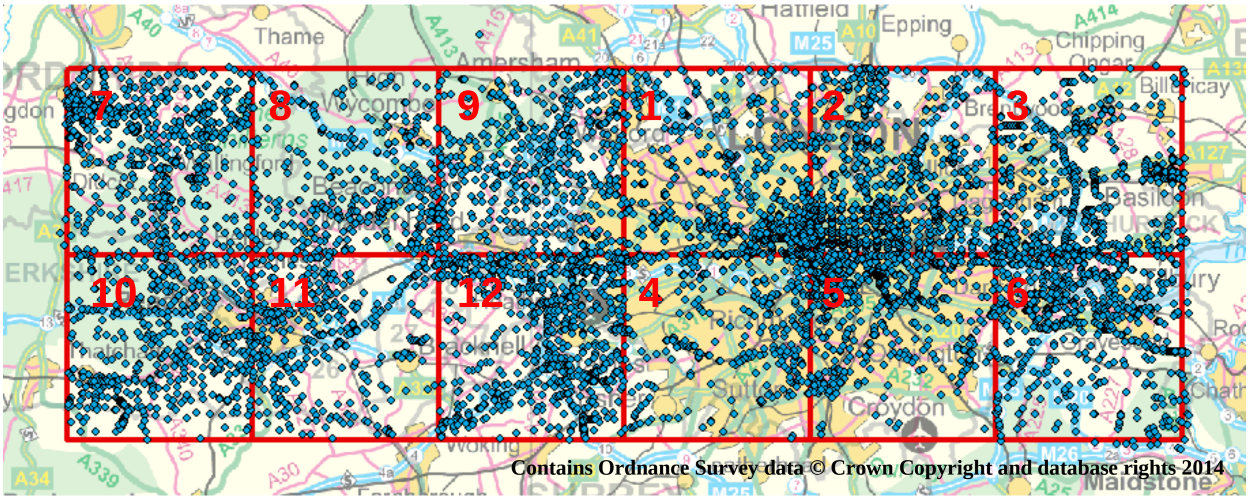

Figure 4 Location of borehole logs consulted in model construction

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. Tiles 1-6 initially used a DTM with a cell size of 25 m, and tiles 7-12 were constructed using a 50 m DTM.

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

4.4 LEGACY AND OTHER 3D MODEL DATA

4.4.1 Thames Gateway models

Tiles 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 tiles 2, 3, and 5, the Thames Gateway model data was not incorporated but was replaced by the London Basin model.

In Tile 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.

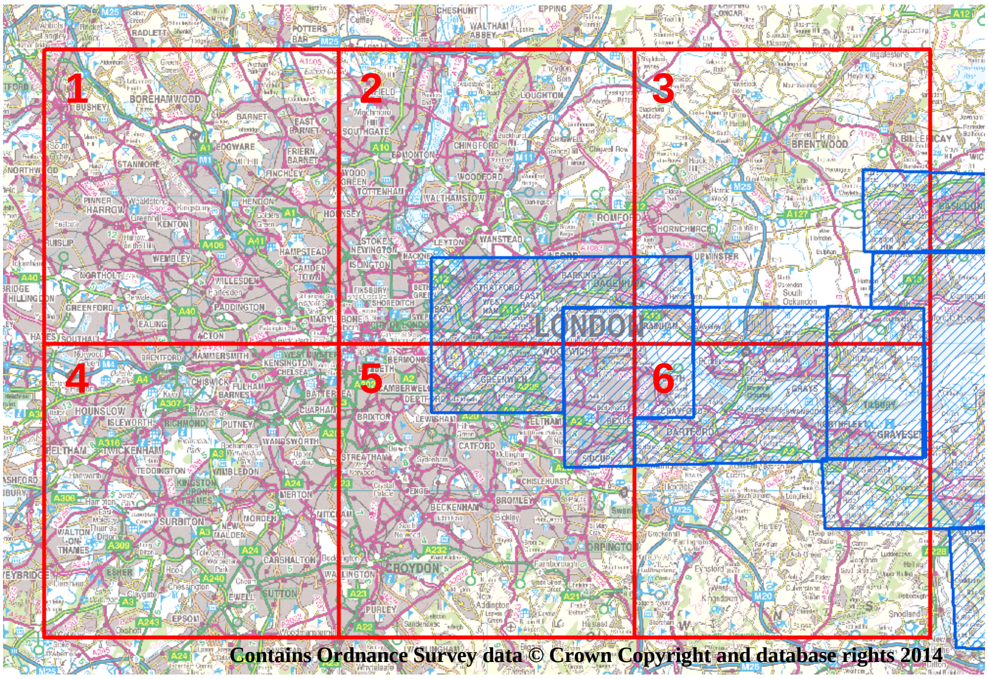

Figure 5 The Thames Gateway models, shown in blue hatching

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 in tiles 1 and 9. 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, and this was not carried over into the revision of the London Basin model.

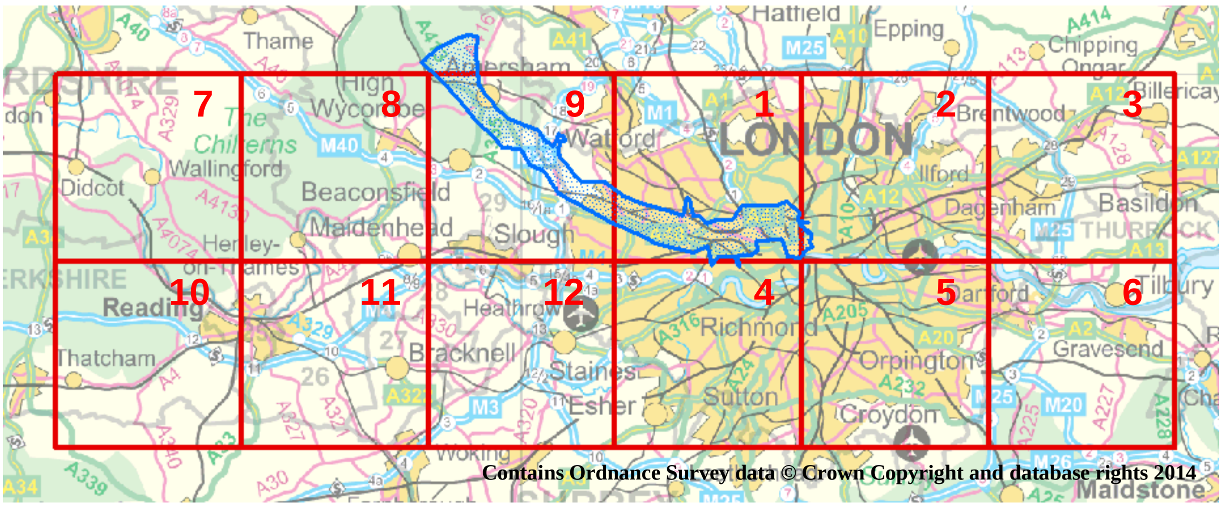

Figure 6 The LithoFrame 10 HS2 route model area, shown in blue stipple

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 (Royse et al. 2010) 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 current basin model.

The eastern half of the London Basin model coincides with the LOCUS model developed by BGS 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, such as in embankments and cuttings along transport routes, reservoirs, etc. 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 in the model 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 model 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 tiles 1–6) or 50 m (tiles 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 GSI3D 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.

A standard GSI3D workflow (Kessler & Mathers 2004; 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, H Burke	2012	2014

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 volume 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.

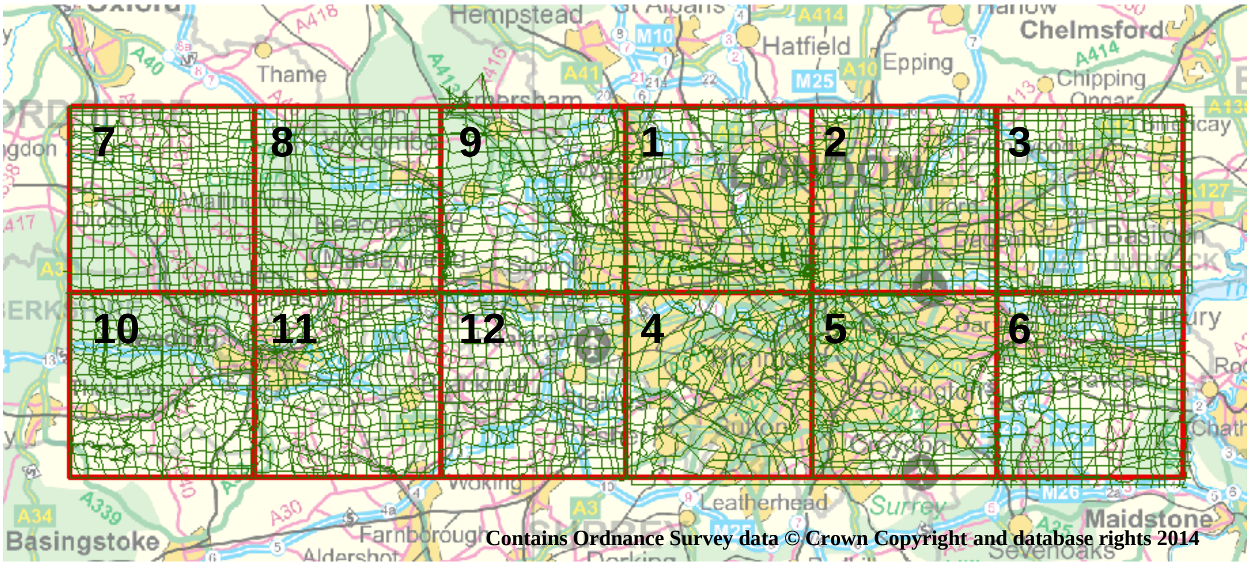

Figure 7 Framework of cross-sections used to construct the GSI3D model

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 iterating 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. Therefore, 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 surveyed more recently, and the entire polygon was modelled as the Winter Hill Gravel Member.

Tidal deposits were modelled in the south-east corner of Tile 3 in accordance with the geological map of the Thames Estuary (Sheet 272, Chatham). However, these tidal deposits continue south onto Tile 6 and westwards on either bank of the River Thames as far as Silvertown, they are not differentiated from the alluvium elsewhere in the model. So to ensure consistency across the model, tidal deposits were reassigned to alluvium in Tile 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 tiles 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

The final version of the combined model is *LL50k_Area1_to_12_v204.gsipr.*

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' (an abbreviation of alluvium) was used in the London GVS to define the base of all alluvium deposits, whereas the Thames Gateway model separated out 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. This revised GVS is named *Areas1_12_Quaternary_GVS.* 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 (colour legend) file applies to the region as a whole, and is also 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, named *Areas1_12_Quaternary_GLEG*.

5.6 EXPORT OF BEDROCK GEOLOGY DATA TO GOCAD®

For each bedrock unit in the GSI3D model, the interpretations in the cross-sections 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.

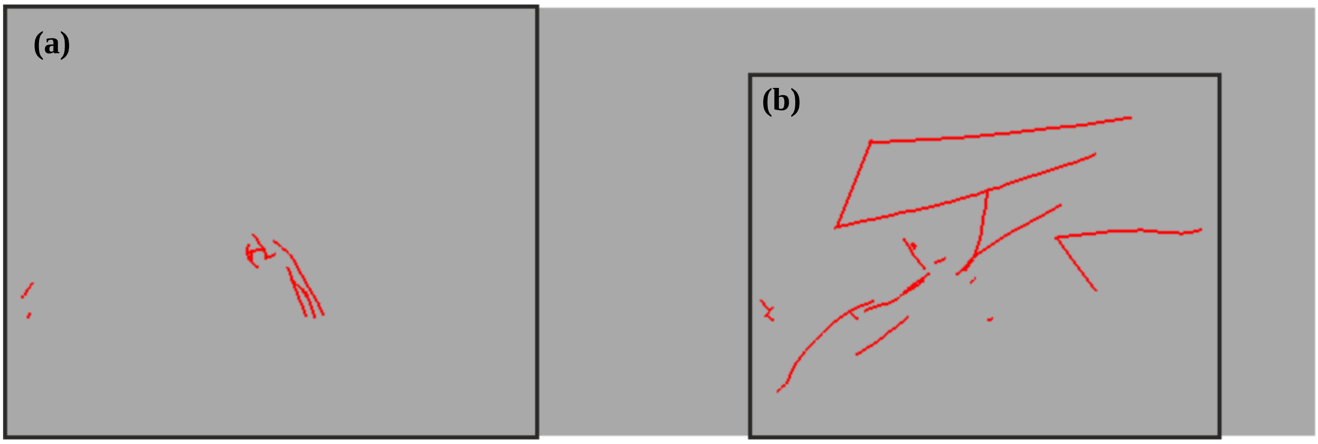

Figure 8 Overview of fault pattern, with the eastern (a) and western (b) faulted areas shown

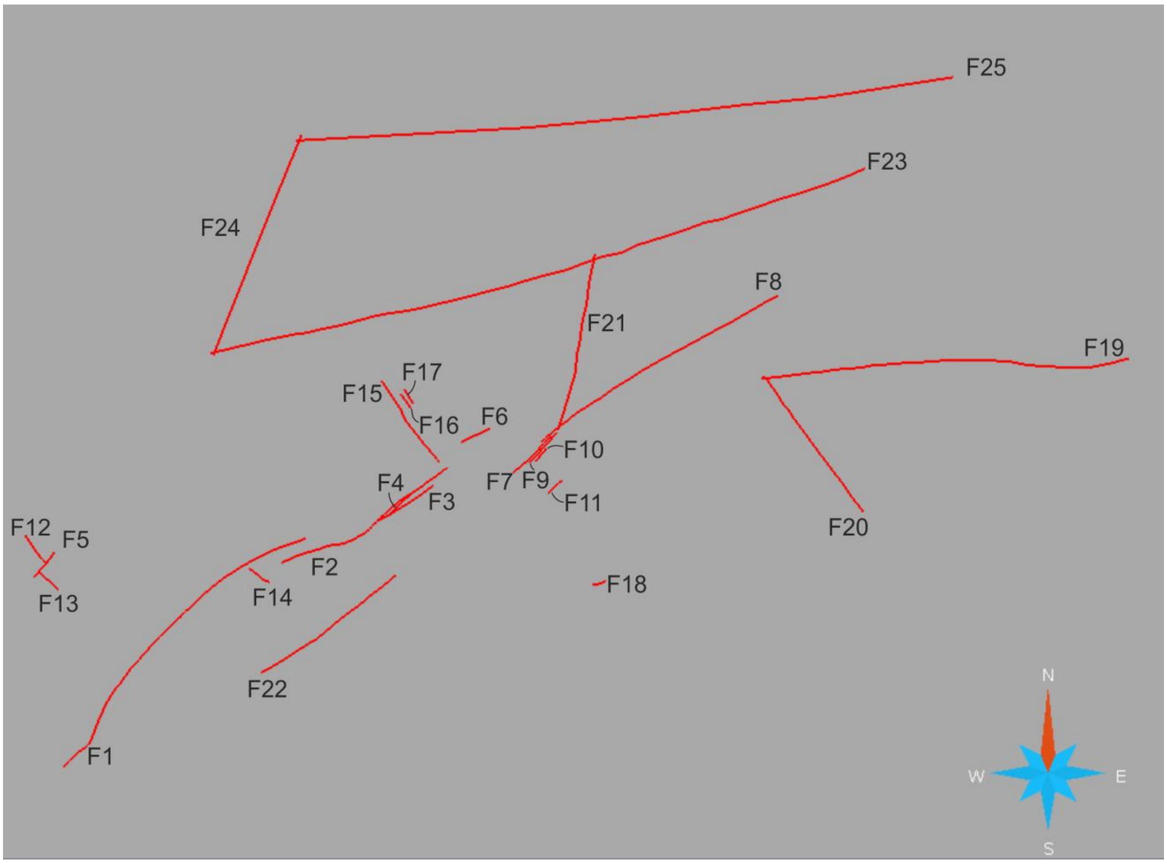

Figure 9 The eastern fault area with faults in the model labelled

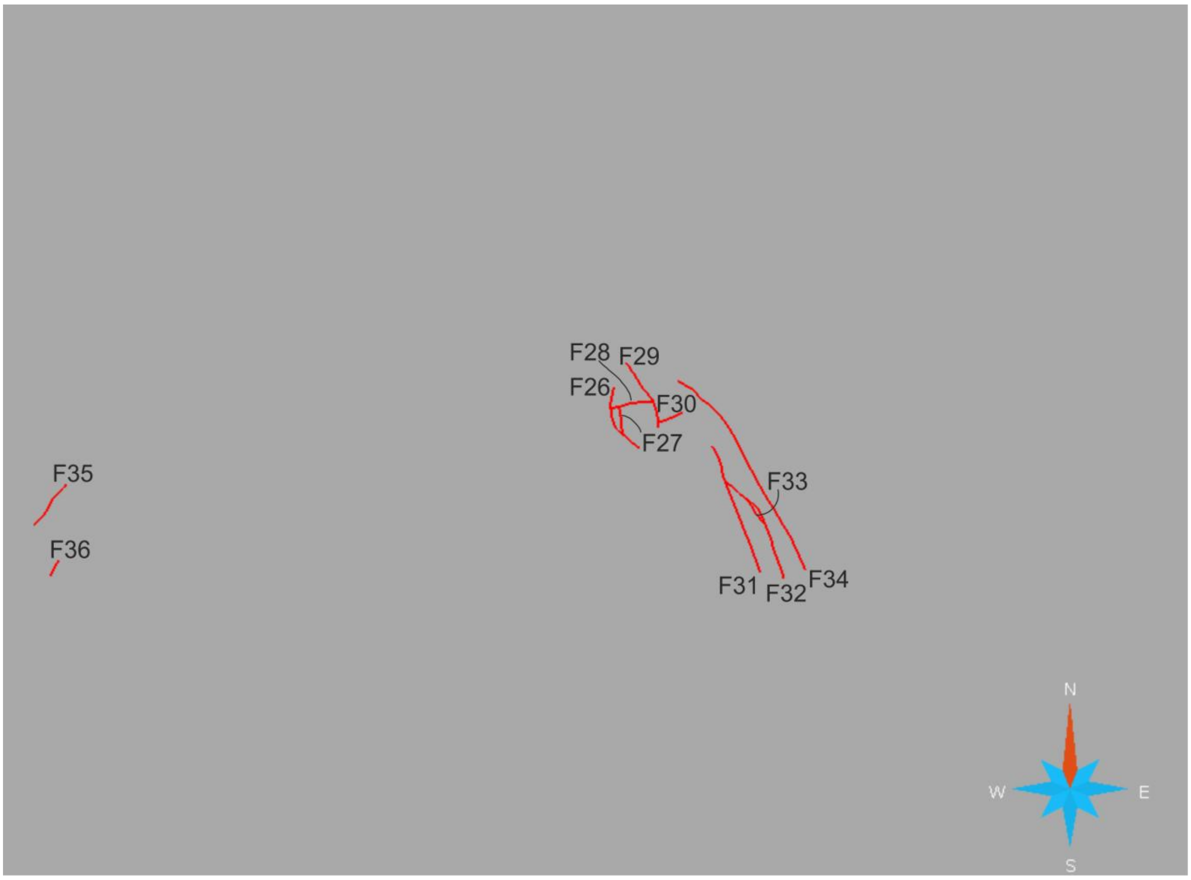

Figure 10 The western fault area with faults in the model labelled

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 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 were straightforward to obtain. 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

Because 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 in 7.1 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 correctly the contacts between faults; 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).

The faults that are modelled are those which have been observed or inferred in the shallow subsurface; others may exist that have not yet been seen, or incorporated into the model. Faults have been extrapolated downwards into the underlying strata, where their form and extent is not known with certainty, although they are probably steeply-dipping structures.

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.

5.9 PRE-EXISTING STRATIGRAPHIC SURFACES ADDED TO THE MODEL

The Chalk Group, Gault and Upper Greensand (combined), Lower Greensand and Base Jurassic bedrock surfaces were constructed using SKUA-GOCAD™ 2013.1. These were constructed as unfaulted surfaces and used the following data which included the rockhead model produced from the London Lithoframe 1:50 000 scale model which gave the relative elevation for the mapped outcrop, DigMapGB 1:50 000 mapped bedrock to constrain the surfaces at outcrop, and cross-section correlation points from National Fence Diagram (GB 3D 2014). All of the surfaces apart from the Base Jurassic were also fitted to deep boreholes from the BGS Stratigraphic Surfaces database.

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 borehole 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 most significant changes are to the pattern of subcrop of the bedrock units at rockhead.

As described above the artificial ground units were updated specifically for the model and have 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.

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.

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.

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

7 Model images

Figures 11 and 12 show views of the units as modelled in GSI3D

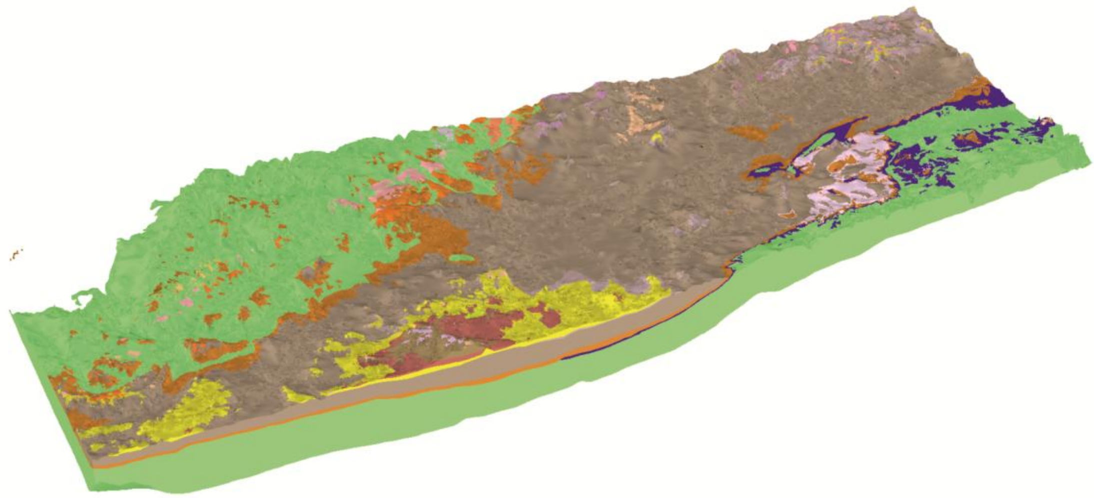

Figure 11 The bedrock units to the base of the Chalk (in green) as modelled in GSI3D, viewed from the southwest. The legend is shown in Figure 2.

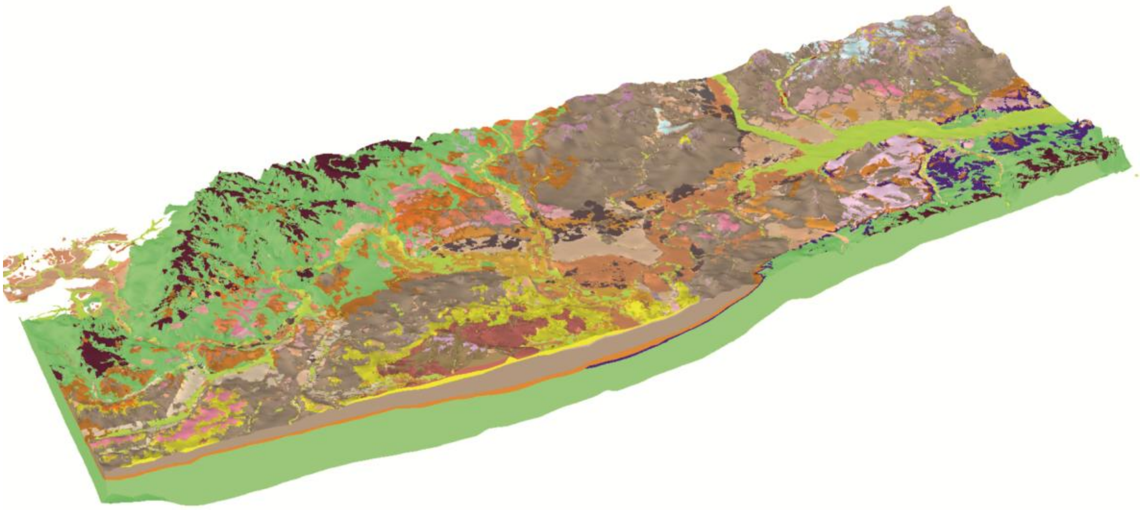

Figure 12 The GSI3D model of bedrock and superficial deposits, viewed from the southwest.

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 (Figure 13). This rockhead elevation surface has a cell size of 100m and caps the bedrock part of the geological model. It was generated by calculating in GSI3D using the complete superficial and anthropocene model on a tile by tile basis, buffering each area by 200m to ensure a small overlap. The resulting rockhead surfaces were combined into the single surface in GIS. Where modelled anthropocene and/or superficial deposits are absent, this rockhead elevation surface corresponds to the Digital Terrain Model. This surface was calaculated in GSi3D and exported to GOCAD® in order to cap the model of the faulted bedrock units.

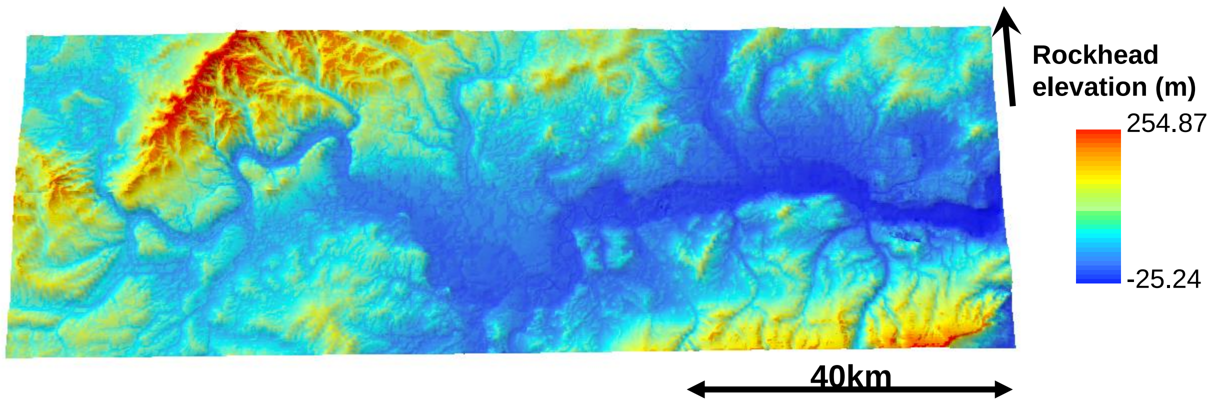

Figure 13. 3D view of the calculated rockhead elevation surface calculated as an ascii grid with a 100m cell size. The highest elevations are in red and the lowest in blue, vertical exaggeration is x 10.

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 6. 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.

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

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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.

England and Wales sheet 258-259 Southend and Foulness. Original survey at one inch scale published in 1868, with drift added in 1871, with revisions in 1883. Resurveyed at six inch scale by C R Bristow, G W Green, M R Henson and R D Lake in 1968 and 1971-72 by S C A Holmes and W A Read.

England and Wales sheet 269 Windsor. Original survey at 1:63,360 scale in 1861-62 with Drift added in 1871 and 1887. Resurveyed at 1:10,560 scale in 1902 and 1910-11; partly resurveyed at 1:10 000 scale by I T Williamson, A Smith, R A Ellison, R T Mogridge, P J Strange, A J M Barron and A J Humpage in 1996.

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. Resurvryed 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.