



## A geological model of London and the Thames Valley, southeast England



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### ABSTRACT

Many geological survey organisations have started delivering digital geological models as part of their role. This article describes the British Geological Survey (BGS) model for London and the Thames Valley in southeast England. The model covers 4800 km<sup>2</sup> and extends to several hundred metres depth. It includes extensive spreads of Quaternary river terraces and alluvium of the Thames drainage system resting on faulted and folded Palaeogene and Cretaceous bedrock strata. The model extends to the base of the Jurassic sedimentary rocks.

The baseline datasets used and the uses and limitations of the model are given. The model has been used to generate grids for the elevation of the base of the Quaternary, the thickness of Quaternary deposits, and enabled a reassessment of the subcrop distribution and faulting of the Palaeogene and Cretaceous bedrock units especially beneath the Quaternary deposits.

Digital outputs from the model include representations of geological surfaces, which can be used in GIS, CAD and geological modelling software, and also graphic depictions such as a fence diagram of cross-sections through the model. The model can be viewed as a whole, and be dissected, in the BGS Lithoframe Viewer. Spatial queries of this and other BGS models, at specific points, along defined lines or at a specified depth, can be performed with the new BGS Groundhog application, which delivers template-based reports.

The model should be viewed as a first version that should be improved further, and kept up to date, as new data and understanding emerges.

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### 1. Background

In recent years many geological survey organisations have started delivering digital geological models in addition to maps as part of their primary underpinning national geoscience knowledge base (Berg et al., 2011). This maps to models migration is well underway at the British Geological Survey (BGS) and this article describes a new substantial 3D geological framework model extending to several hundred metres depth for London and the Thames Valley in southeast England. This is one of the first extensive models of the shallow subsurface to be released by BGS; others are available for the Ipswich-Colchester area of East Anglia, and parts of York and Greater Manchester (Mathers, 2012, 2013; Burke and Price, 2013; Bridge et al., 2010).

Digital geological framework models are representations that convey the three dimensional arrangement of the geological units present, they are capped by a surface geological map at a

corresponding scale, draped onto a digital terrain model. The models (also called 3D maps) are built by assembling all the types of available data (boreholes, maps, sections, geophysics, etc.) in their correct spatial positions to enable an interpretation or understanding of the 3D distribution of the units to be reached. This facility to visualise the interplay of complex spatial datasets that otherwise the human brain could not resolve with ease is one of the advantages of the application of modern digital technology to geological data.

Unlike a 2D digital geological map with a cross-section, geological framework models contain knowledge at any point in x, y and z dimensions. This means that they can be interrogated to provide a geological answer anywhere, for example at a point, along a defined alignment or at a specified depth; outputs from such queries include synthetic borehole or section prognoses. In addition geological models define the subsurface distribution of all the geological units, thereby enabling subcrop limits of all units to be established and the geology to be uncovered layer by layer. More advanced outputs include isopach maps for individual or combined units and contours on all buried surfaces.

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Perhaps most importantly the finished model is a very powerful way of visualising and communicating the geological understanding to an expert, a decision maker, a geoscience student or the general public alike, whilst also helping develop solutions to real-life geological and environmental problems.

## 2. Geology of the model area

The area modelled comprises 4800 km<sup>2</sup> covering London and the Thames Valley extending westwards as far as Newbury and eastwards to the inner Thames Estuary (Fig. 1). It stretches from easting 450 000 to 570 000 and from northing 160 000 to 200 000 and extends to a variable depth of several hundred metres, the precise depth being defined by the geology. The model has been built in stages since 2006 using funding from the BGS National Capability budget. Although the region is heavily studied, as Aldiss (2013), and Aldiss et al. (2014) have pointed out much remains to be discovered about the deeper geological structure, distribution of faulting, and neotectonics of this important region.

An overview of the regional geology is provided by Sumbler (1996), whilst the 'London Memoir' (Ellison et al., 2004) describes the four 1:50 000 scale mapsheets covering London and environs that form the eastern half of the model area. More recently, Royse et al. (2012) have also reviewed aspects of the geology of London. The western parts of the modelled area have been recently geologically surveyed, including the districts around Reading (Mathers and Smith, 2000), Windsor (Ellison and Williamson, 1999), Newbury (Aldiss et al., 2006), and Beaconsfield (Morigi et al., 2005).

The major bedrock structure of London and the Thames Valley is the northeast to southwest trending London Basin synclinorium (Sumbler, 1996; Ellison et al., 2004). This structure formed in Palaeogene times and terminated during the Oligocene to mid-Miocene regional compression that in southeastern England represents the main Alpine orogenic event. Onshore, the outcrop of the Late Cretaceous Chalk Group forms a rim around the younger strata of the London Basin. The Chalk, which is over 200 m thick beneath London, is the region's principal aquifer. It is famous historically for its artesian flow from water wells sunk near the

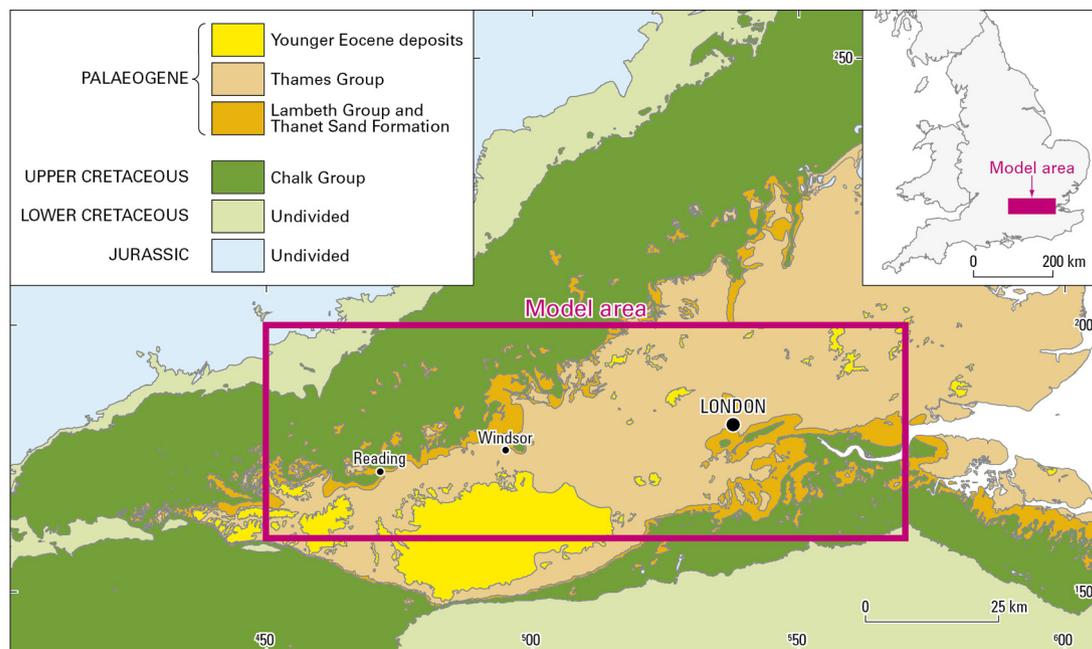
**Table 1**

Stratigraphy of the Palaeogene bedrock units. The units modelled are shown in bold.

Group	Formation	Member
Bracklesham Group	<b>Camberley Sand Formation</b>	
	<b>Windleham Formation</b>	<b>Stanners Hill Pebble Bed</b>
	<b>Bagshot Formation</b>	<b>St Anne's Hill Pebble Bed</b>
		<b>Swinley Clay Member</b>
Thames Group	<b>London Clay Formation</b>	<b>Claygate Member</b>
	<b>Harwich Formation</b>	
Lambeth Group	Reading, Woolwich and Upnor Formations	
	<b>Thanet Sand Formation</b>	

centre of the Basin and for its susceptibility to collapse due to dissolution. In the model the Chalk is undivided although in some parts of the area formation level classification has been modelled in separate studies (Royse, 2010; Royse et al., 2010). Beneath the Chalk the Upper Greensand locally overlies the Gault Formation which present across the whole area comprising stiff grey clay, the two units are grouped within the model. They rest on the Lower Greensand Group, the Wealden Group and Jurassic sedimentary rocks, these latter units are only present in the southern, western and northwestern parts of the model.

Overlying the Chalk, the oldest Palaeogene deposit is the Thanet Sand Formation (Table 1). This consists of a coarsening-upwards sequence of glauconitic fine-grained sands and silts, with a basal bed of flint cobbles and of nodular flints derived from the Chalk. The Thanet Sand Formation reaches a maximum thickness of around 40 m in the east of the area but thins rapidly westwards to where it is overlapped by the Palaeocene to Eocene Lambeth Group beneath western London. This lithologically variable group is up to 30 m thick in the area, consisting of variable proportions of sands, silts, clays and gravels (Ellison, 1983). The overlying Eocene sediments, the Thames Group, consists of the London Clay Formation, underlain in much of the eastern part of London by the Harwich Formation. This has only been differentiated in the



**Fig. 1.** The bedrock geology of the London Basin and location of the modelled area. Geological linework from DigMap 250K bedrock version 4.11 BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2014.

model where it consistently exceeds 2 m in thickness; thinner occurrences are reported farther west but due to the practicalities of modelling at the current resolution these are included within the overlying London Clay. The Harwich Formation consists predominantly of sand and pebble beds, which, in southeast London, are locally up to 12 m thick. The London Clay Formation comprises up to 150 m of grey to blue-grey, bioturbated, silty clay, with sandy or pebbly beds at some levels. It includes the alternating sand-clay sequence of the Claygate Member at the top, which has been modelled as a separate unit (Table 1). The London Clay sequence contains more sand and sand interbeds in the westernmost parts of the area although this distinction has not been modelled. Younger Eocene sediments include the sandy Bagshot, Windlesham and Camberley Sand formations, with the three units locally reaching a total thickness of around 70 m. These units tend to occur as outliers, capping some of the highest hills within the central London Basin. Thin units within the sequence comprising the St Anne's Hill and Stanners Hill Pebble Beds, and the Swinley Clay Member have been modelled as separate units although each has an extremely restricted geographical distribution (Ellison and Williamson, 1999). An isolated patch of Neogene Lenham Beds is also present just west of Rochester, in Kent.

In total, 64 superficial and artificial units were modelled. These include substantial flights of river terrace deposits in each of the major elements of the drainage network (Thames, Loddon, Kennett, Lea, Mole, Wey, etc.) and mainly follow the classification on the corresponding BGS 1:50 000 scale mapsheets. Locally, patches of fine grained overbank silts and clays are preserved on these terrace aggradations (e.g. Langley Silt). These may, in some cases, also contain an aeolian or loessic component. The extensive terrace flights attest to the substantial downcutting of the Thames system during the Pliocene and Quaternary probably in response to gradual uplift onshore and subsidence in the southern North Sea Basin (Gibbard, 1988; Mathers and Zalasiewicz, 1988). Major syntheses of the evolution of the Thames drainage system and its terraces are given by Gibbard (1985, 1994) and Bridgland (1994).

On the published 1:50 000 scale BGS maps of the region small patches of till relating to the Anglian glaciation occur in north London and polycyclic Head and Clay-with-flints deposits are widespread. The term Head encompasses slope or colluvial deposits of diverse character, the Clay-with-flints is present resting on Chalk bedrock, it is probably derived from remnants of Palaeogene deposits and its genesis probably dates back to the Neogene. Holocene deposits mainly comprise alluvium along the current river valleys and the intertidal silts and clays of the Thames Estuary. The boundary between the two is likely to interdigitate. Artificially modified ground (AMG) follows the classification of the DigMapGB-50 dataset (see Fig. 4); however the distribution has been substantially upgraded in the modelling as described below.

### 3. Building the model

A detailed account of the data used and methodology employed in constructing the model is contained in Burke et al. (2014). Here we offer a brief summary of these aspects and consider the wider impacts of the model.

#### 3.1. Baseline data

With the abundance of shallow borehole data held by BGS for the model area it is simply impractical from a resource point of view to consider encoding the dataset with the stratigraphical classification needed for modelling. In total BGS holds about 100 000 borehole records for the modelled area, the vast majority are shallow boreholes occurring in clusters due to site investigation or along linear routes. The borehole information considered includes that encoded by the earlier studies of Ellison et al. (1993), Strange et al. (1998) and deeper boreholes with detailed records to help constrain the deeper geological units. A GIS was then used to ensure an even distribution of boreholes wherever the data made this possible. Where available additional boreholes were then selected for classification to infill the data poor areas. Selection criteria were drilled depth, borehole location and level of detail in the borehole log.

In total, 7174 encoded borehole logs were considered in the construction of the GSI3D cross-sections (Fig. 2). These data were downloaded from the BGS corporate databases, which automatically generates model-ready files. The retrieval captures every entry in the BGS Borehole Geology database. Some individual borehole records have been encoded for different purposes at different times, and so the database contains multiple interpretations for some boreholes. These multiple entries were then filtered on a priority basis in terms of their reliability and the detail recorded.

Geological map linework (as ESRI shape files) was selected from the BGS DiGMapGB-50 dataset. This extract was checked for inconsistencies at the 1:50 000 mapsheet boundaries, and the linework was rationalised wherever possible with precedence usually given to the more recent survey and nomenclature.

The model is capped and fitted to a BGS-produced 'Bald Earth' Digital Terrain Model (DTM) with a 100 m cell size. This DTM is based on the BGS licenced NextMap DTM but has Ordnance Survey Landform Profile data inserted for extensive wooded areas where this was found to provide a better representation of the actual ground surface.

Existing BGS models, memoirs and reports together with published literature guided the modelling throughout and included the extensive use of georeferenced scans of sections and maps from Ellison et al. (2004) and Sumbler (1996). There is limited seismic data for the area, and this, together with regional

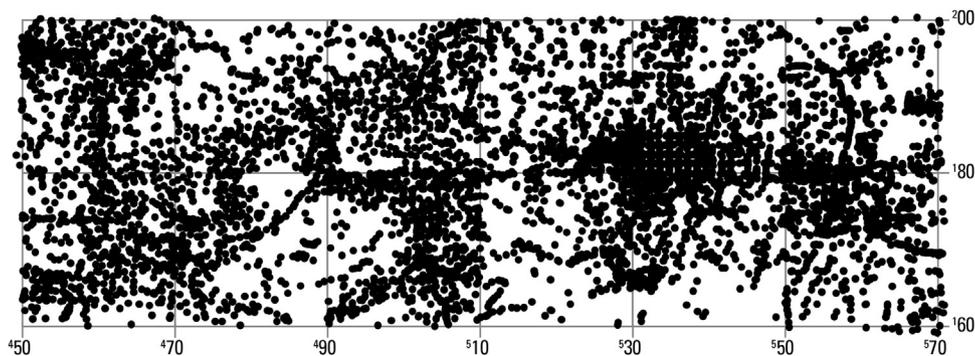


Fig. 2. Location of borehole logs used to inform the model.

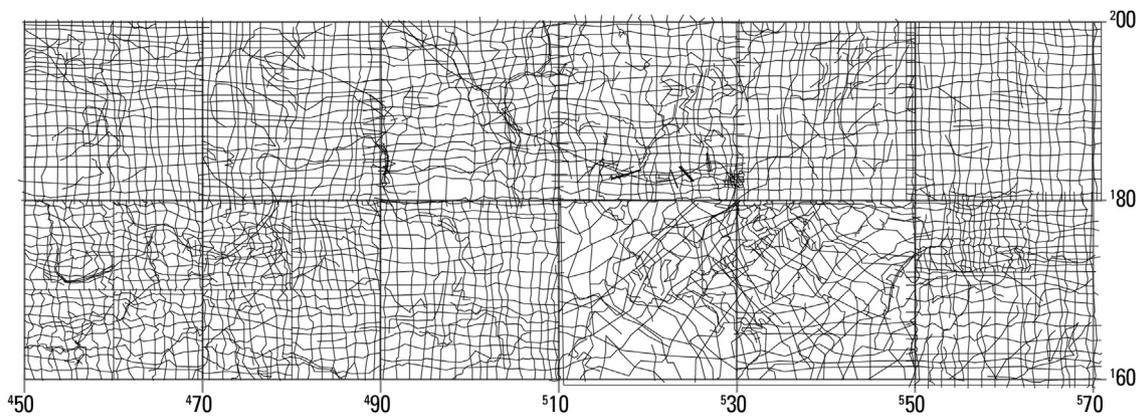


Fig. 3. Framework of cross-sections used to construct the GSI3D model.

geophysical surveys are useful to inform the structure of the older strata and basement mainly at depths greater than the base of the present model.

### 3.2. Modelling the geology

The Quaternary and Palaeogene bedrock geology were initially modelled in GSI3D following the standard methodology (Kessler and Mathers, 2004; Kessler et al., 2009). This involves the drawing of numerous cross-sections to form a framework and then mapping out the extents of each of the geological units present using their map outcrops together with their subcrop extents as defined in the sections. The calculation of the surfaces of the geological units is by interpolation between cross-sections and the unit extents. The framework of 922 cross-sections constructed is shown in Fig. 3, the regular spacing between sections is 1–2 km with a maximum of about 3 km.

Although the DiGMapGB-50 dataset formed the initial surface geology for the modelling process the final model has slightly modified and updated this geological interpretation. These changes however have not yet been incorporated into the current version of the DiGMapGB-50 dataset.

Because of the varied dates of the surveys in the modelled area a variable approach to the representation of AMG is apparent in the DiGMapGB-50 dataset. Some sheets record AMG, others do not. To try and address this inconsistency a GIS-based desk study was carried out to identify instances of AMG that were not present in the DiGMapGB-50 data. This involved examining modern 1:10 000 scale topographic maps for areas where the ground surface has been modified, such as in embankments and cuttings along transport routes, reservoirs, and other evidently man-made features. The revised distribution is presented in Fig. 4 for the whole model area and as an example of the level of detail an inset map for the Dartford area is included with all the five main categories of AMG occurring in juxtaposition. To date this updated information has not been incorporated into the current released version of DiGMapGB-50.

However, despite this enhancement the AMG still remains poorly represented in both DiGMapGB and in this model dataset due to the difficulty of defining the extensive areas of it that are not associated with specific landforms. Mapping this 'urban blanket' still needs to be achieved and will involve examining very large numbers of borehole records.

Discontinuous thin superficial deposits such as Clay-with-flints and Head, and all AMG units are represented in the model as 2D polygons (extents) and are drawn in the cross-sections. However their complex shapes and discontinuous nature would require extensive construction of additional short cross-sections in order to

provide sufficient geometric control with which to calculate reliable 3D volumes.

The fault network resolved at the intended model resolution was initially established in GSI3D by 3D visualisation of the data to detect significant offsets of the strata (Ford et al., 2008, 2010). In order to create the faulted surfaces of the bedrock geological units, the interpreted sections, the unit extents and the faults were then exported to GOCAD<sup>®</sup>, where a standard workflow for model construction was used to generate the faulted surfaces. To cap the GOCAD<sup>®</sup> model, the rockhead (base Quaternary) surface was exported from GSI3D as an ASCII grid with a cell size of 100 m.

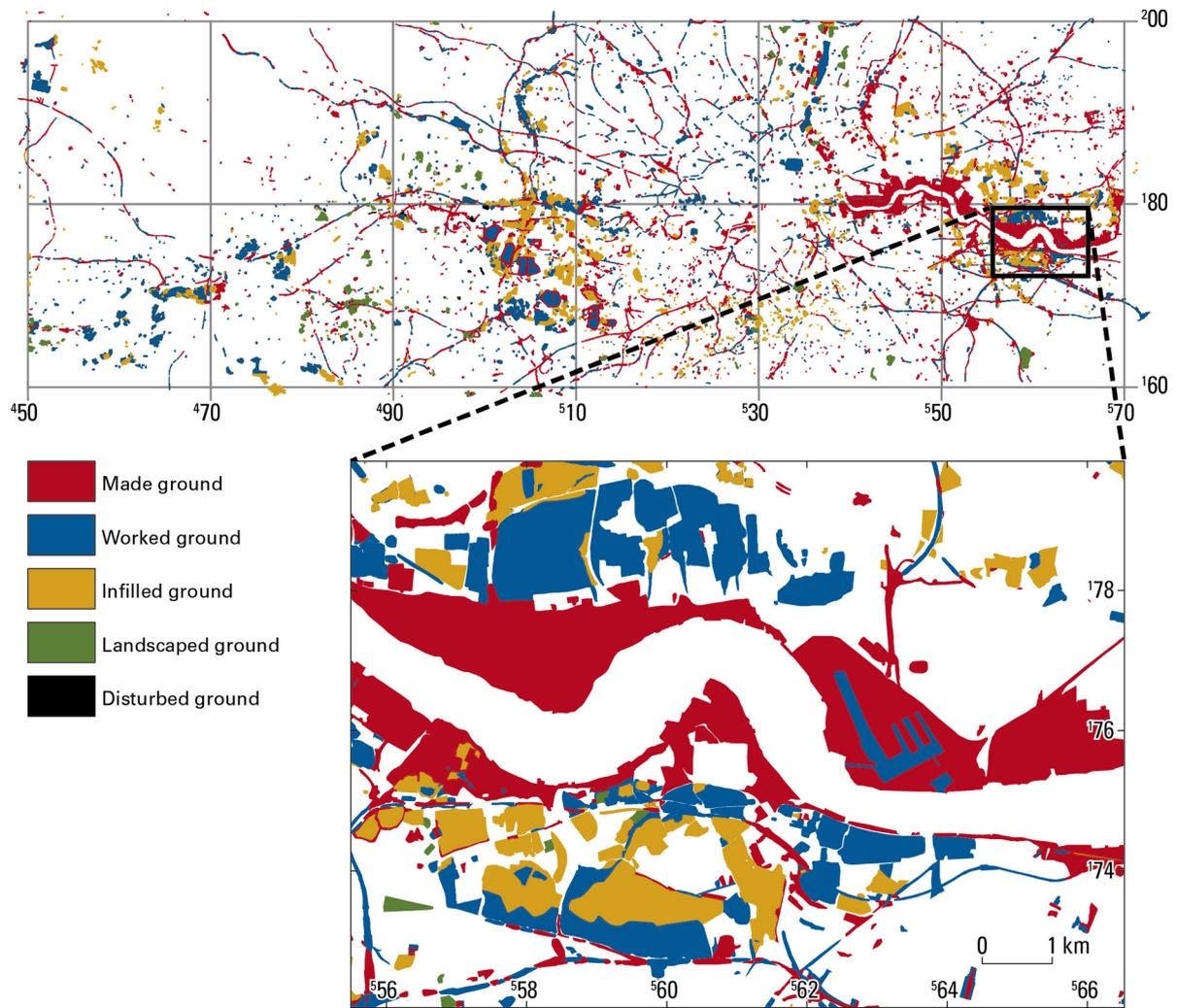
Gridded surfaces defining the bases of four additional older geological units were finally added to the model to ensure that model coverage to a minimum depth of several hundred metres was achieved throughout. These additional surfaces were generated from a lower resolution unfaulted model of the whole London Basin developed in GOCAD<sup>®</sup> and based on deep boreholes and the sections in the GB3D national bedrock model (Mathers et al., 2014). The surfaces comprise the base of the Chalk Group, the base of the combined Gault and Upper Greensand, the base of the Lower Greensand and the base of Jurassic strata. The interval between the lowest two bases (Lower Greensand and Jurassic) contains both Lower Cretaceous Wealden strata and Jurassic sedimentary rocks. These lower resolution deeper surfaces were adjusted bearing in mind their controlling borehole data to ensure an overall structural conformity with the interpretation reached for the overlying strata.

The base of the model is always defined by the oldest modelled geological surface present, rather than the model base being defined at a constant depth. In the northeastern parts of the model the lowest modelled unit present (usually the Gault and Upper Greensand) rests directly on the Palaeozoic basement rocks of the London Platform whereas in the south and western parts of the model older Mesozoic sedimentary rocks generally underlie the modelled stack.

### 4. New understanding from the model

The modelling process involves the assembly of a workspace containing all the relevant geoscience datasets in their correct spatial positions. This enables the modeller(s) to comprehend and visualise the complex spatial relationships between multiple datasets in order to arrive at an interpretation.

The model outputs include a revised rockhead surface (Base of Quaternary) depicted in Fig. 5. Where Quaternary deposits are absent the rockhead surface lies at the ground surface as defined by the digital terrain model. The highest elevations are in shades of red along the Chiltern Hills in the northwest, and the North Downs



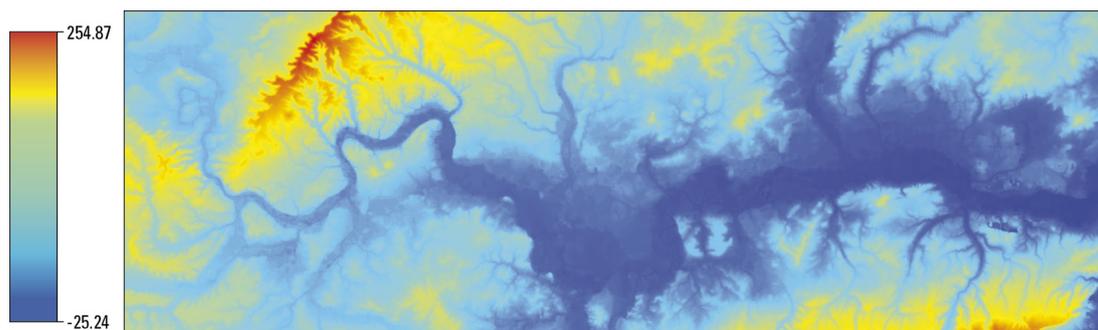
**Fig. 4.** Artificially modified ground coverage for the whole model area and below for the small inset area straddling the Thames at Dartford. Extensively modified from DigMapGB-50 artificial version 7.22 BGS © NERC.

in the southeast of the model area. The channels beneath the modern river floodplains form the lowest elevations descending to  $-25$  m OD and are shown in dark blue.

A related output is the production of a revised grid of the thickness of the Quaternary deposits shown here in Fig. 6. It shows that most of the thickest deposits in shades of red underlie the lower reaches of the Thames channel and also occur as isolated anomalies farther west perhaps relating to large scour hollows or depressions. The white areas indicate the absence of mapped Quaternary deposits.

The new rockhead model has in turn enabled a reassessment of the subcrop pattern of the bedrock units including a revised fault network for the Greenwich Fault Belt and adjacent areas (Ford et al., 2008, 2010, and Fig. 7). More recent work suggests the presence of considerably more faults under London than those shown at present (Aldiss, 2013) and this and other studies will need to be assessed and incorporated into future versions of the model.

In addition the model can be used to generate contoured surfaces for the top and base of individual river terrace deposits, or



**Fig. 5.** The Rockhead (base Quaternary) surface grid calculated from the model.

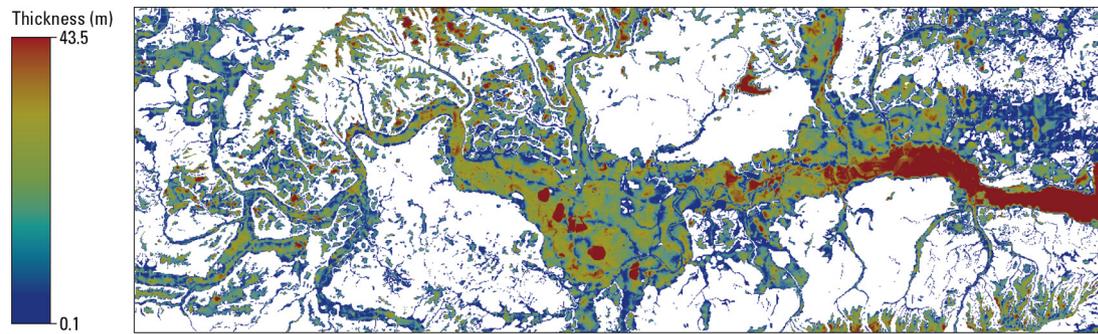


Fig. 6. A calculated thickness grid of the modelled Quaternary deposits.

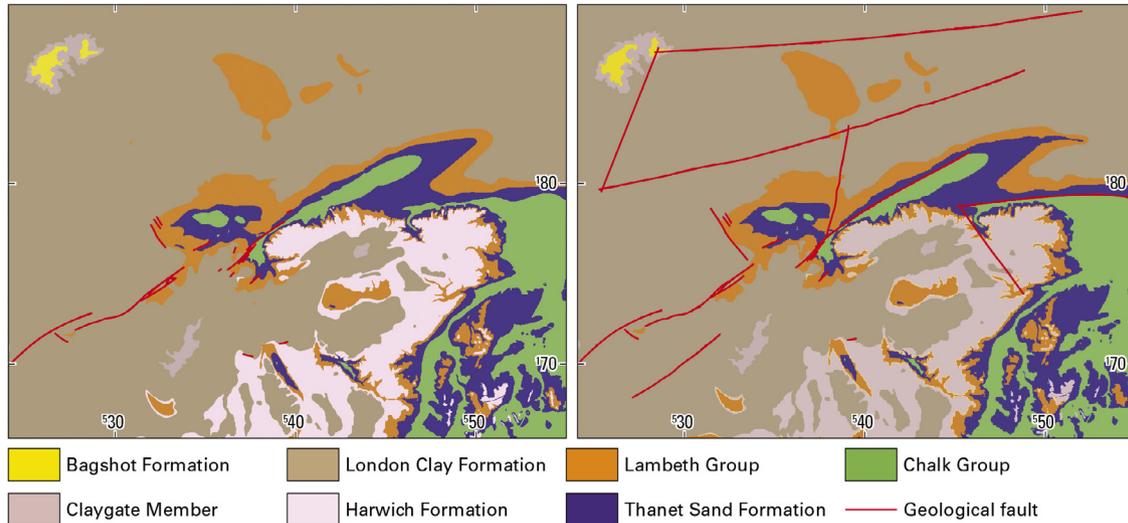


Fig. 7. Revision of bedrock geology in the London area. Left, the interpretation from the current DigMapGB-50 bedrock version 7.22 BGS © NERC. Right, revision following 3D visualisation and modelling featuring the new pattern of faults reported by Ford et al. (2008, 2010) and further changes to the bedrock unit coplines.

of any other unit, and so it has the potential for testing the validity of proposed terrace classifications and correlations within the Thames system. A further advantage is this data can be viewed in the 3D window of any modelling software or viewer at any vertical exaggeration and from any angle rather than using the traditional 2D plots of elevation along the thalweg.

Fig. 8 shows a fence diagram of synthetic sections with a 10 km spacing calculated from the completed model. This fence diagram is available as a 3D PDF from the BGS website (see Section 6). It illustrates the broad regional structure and the level of stratigraphic detail found in this model. The thickening of the bedrock sequence into the Wealden and Wessex basins is shown in the southeastern and southwestern corners respectively. Fig. 9 shows the calculated model down to the base of the Cretaceous viewed from the southwest.

## 5. Uses and limitations of the model

Here we list guidance on the appropriate use and limitations of the model. Existing and potential applications of the model are many and varied and the model is intended to be fit for any purpose so long as the use is at an appropriate resolution. Here we review existing applications and outline other possible uses.

### 5.1. Uses

Appropriate uses of the model include the following:

- General and geoscience education to illustrate the regional geology of London and the Thames Valley centred around a resolution of 1:50 000 and within the intended range of 1:25 000 to 1:100 000.
- Genesis of borehole, cross-section and depth slice prognoses from the model delivered via the BGS Groundhog application (see below).
- Use as a framework for the construction of higher resolution, more detailed geological models for site-specific and local studies.

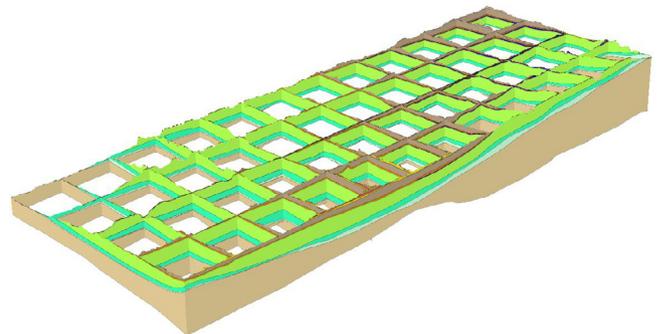
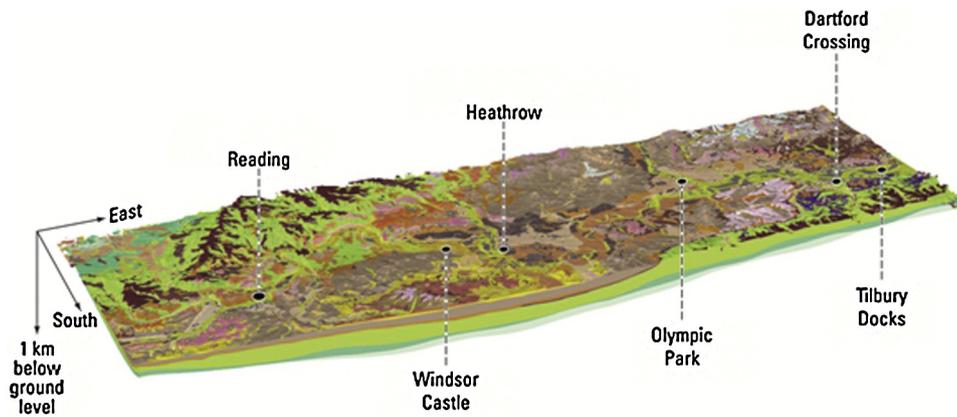


Fig. 8. A fence diagram of auto-generated cross-sections through the model with a 10 km spacing viewed from the southwest. The Vertical Exaggeration is  $\times 10$ . The colour scheme for the Palaeogene and Chalk bedrock units is as shown in Figs. 7 and 10. Beneath the Chalk shown in light green are the Lower Cretaceous deposits in shades of blue and the lowest unit is the Jurassic sedimentary rocks in brown.



**Fig. 9.** The model of bedrock and superficial deposits to the base of the Cretaceous strata, viewed from the south-southwest. The vertical exaggeration is  $\times 10$ . The colour scheme for the Palaeogene and Chalk bedrock units is as shown in Figs. 7 and 10.

- Catchment and regional scale assessments for hydrogeology, planning and mineral resource estimation.
- Derivation of themed outputs and bulk attribution of the geological units in the model with geological properties.

### 5.2. Limitations

Limitations inherent in the model include:

- Any representation or use outside the intended resolution range (1:25 000 to 1:100 000).
- Use for site-specific assessments of any kind (the model is likely to provide a useful guide or starting point for such studies but outputs from the model are not a substitute for them).
- Mineral reserve quantification of any kind. (This involves detailed quantification of the deposit volumes and grades and is beyond the capacity and detail of the current model.)
- The vast majority of the model accepts the available DiGMapGB-50 surface geology, with only minor amendments. However the standard of the DiGMapGB-50 dataset is variable relating to surveys carried out at various points over the last 100 years. A consideration of all the available borehole data would result in substantial revision of the data especially with regard to AMG.
- Discontinuous thin superficial deposits such as Clay-with-flints, Head, and all AMG units are included in the model as 2D polygons and in the cross-sections. Volumes cannot at present be calculated for these units as discussed above so they will be absent from any borehole prognoses or synthetic sections generated from the model by the BGS Groundhog application (see Section 6.3).
- Not every available borehole record was considered in the construction of the model. Some variation may therefore occur between the depth of units modelled and depths recorded in the boreholes that were not used.
- Very localised geological phenomena such as small scour hollows, relict pingo and allied periglacial structures and small channel infills cannot be easily shown at the intended resolution of the model unless a borehole proving the structure is included in a cross-section. For more information on such structures, their genesis and locations see Berry (1979), Ellison et al. (2004, Fig. 35), and Banks et al. (in press).

### 5.3. Existing applications for the model

The scale of the model could be said to be 1:50 000 as it is consistent with the surface geological linework at that scale. However with digital data the facility to zoom in and out makes it

very important to convey the sensible limits to which such zooming can be performed for the data. The term resolution rather than scale is preferred for digital geospatial datasets. So as noted above the intended (safe) resolution range for use of this model is 1:25 000 to 1:100 000. Hence the model cannot provide sufficiently detailed solutions for site- and route-based studies but provides a useful guide or starting point for such studies. Three examples of cases where the model and methodology have already provided a useful framework within which a more detailed or site-specific model was developed in the London area are as follows.

The new underground Farringdon Station in east London is part of a project to build the east–west Crossrail system linking central London with the Channel Tunnel rail link, and Heathrow Airport (Gakis et al., 2014). The station is scheduled for completion in 2016, and comprises two parallel 300 m long platform tunnels c. 11 m wide and up to 37 m apart, connected by cross-passages. To assist with the design and project development a detailed Farringdon geological model was built in 2009–10 based on existing ground investigation undertaken by Crossrail and on third party borehole records (Aldiss et al., 2012). Adjacent cross-sections from the London and Thames Valley model provided the broad stratigraphic framework within which the more detailed Farringdon model was constructed. The Farringdon model included a facies-level subdivision of the Lambeth Group and apparent offsets of this detailed sequence indicated the presence of several faults.

More recently in 2012 a 1:10 000 scale route model was commissioned by HS2 Ltd for the proposed route from Euston north-westwards. This model utilised the London and Thames Valley model as a starting point. An extract of the regional model was densified with extra cross-sections added along the HS2 corridor. These were subsequently incorporated back into the regional model. The HS2 model conveys greater detail in the Anthropogenic deposits and bedrock stratigraphy than the regional model or the DiGMapGB-50 dataset for this area.

A detailed model of the Chalk Group under central London divided it into six component formations; this was developed for the Environment Agency of England and Wales (Royse, 2010; Royse et al., 2010). This model is consistent with the present London and Thames Valley model utilising the same bounding top and base surfaces for the Chalk Group. Further faulting within the Chalk Group was indicated by offsets in the elevation of the various formations in the detailed model.

All these models have successfully developed a more refined lithostratigraphy that keys into the lower resolution units of the regional model; in addition they have also indicated the presence of faults at a resolution that is too high to incorporate satisfactorily

into the overall London and Thames Valley model. This again emphasizes the importance of scale or resolution and fitness for purpose in all aspects of the spatial representation of geological units in maps and model outputs.

5.4. Future enhancement of the model

The model described should be considered as Version 1; as such it marks a significant step for BGS in the migration from the provision of 2D to 3D geological data for London and the Thames Valley. However, the limitations of the existing model are spelt out above; these identify aspects where the model could now be enhanced to provide greater accuracy and reliability.

The chief tasks could include:

- Assessment of available borehole records to ensure revision of the existing surface geology of the area (DiGMapGB-10 and -50)

and especially the distribution of Quaternary deposits and the AMG layer.

- Further assessment of the evidence for faulting across the region and the need for an integrated structural interpretation taking account of all available sources.
- Deployment of software tools to better facilitate the generation of modelled unit volumes for discontinuous superficial deposits such as Head and Clay-with-flints.
- Population of the model with more stratigraphic detail; in particular the division of the Jurassic sedimentary rocks, and further division of the Chalk Group into its component formations and the Lambeth Group into facies.
- Establish editing of the model by continuous revision as new data is acquired involving the participation of users and stakeholders.
- Expanding the coverage of the model to adjacent parts of the London Basin.

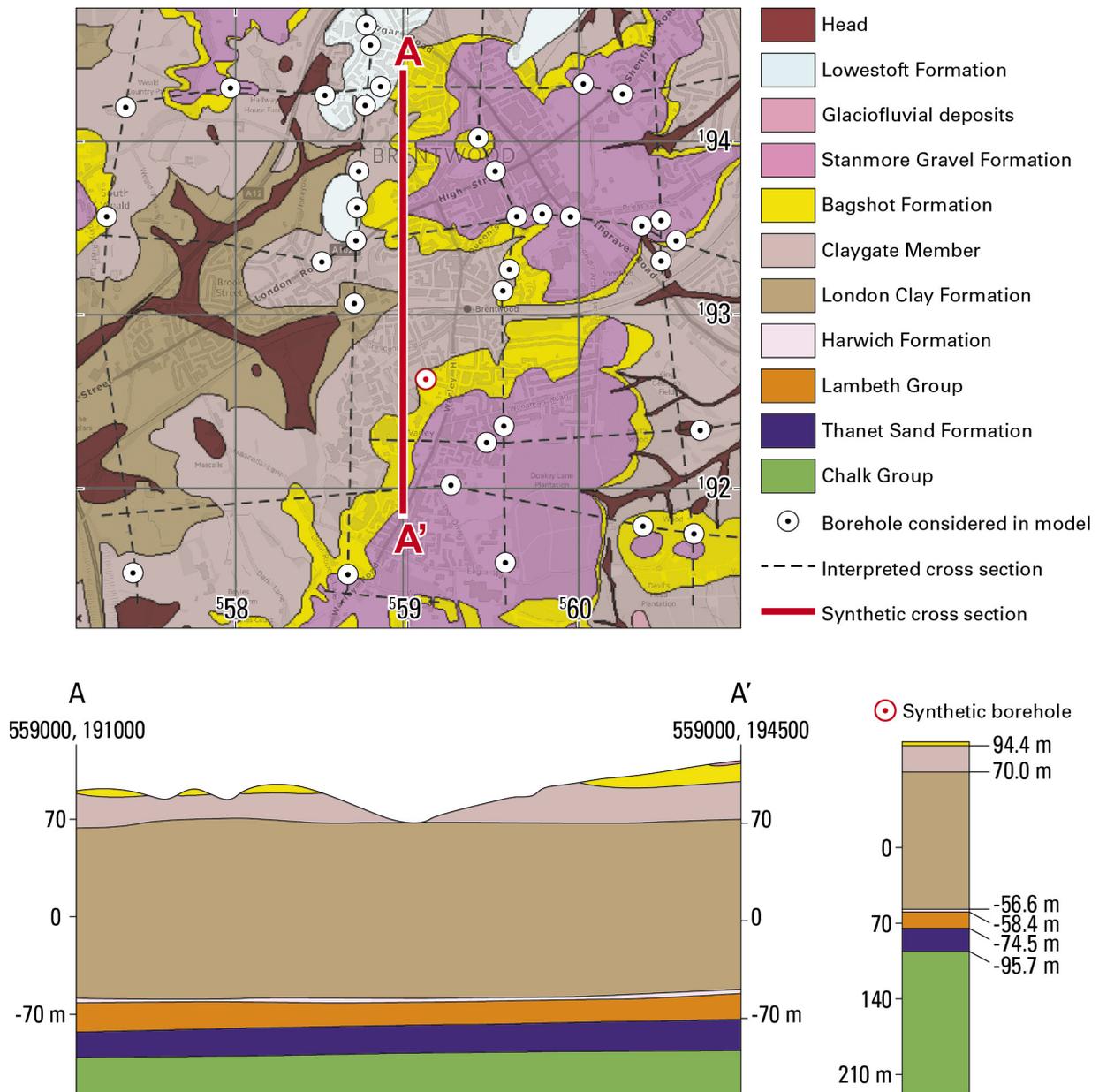


Fig. 10. Auto generated section and borehole from the BGS Groundhog application. NEXTMap Britain elevation data from Intermap Technologies. Contains Ordnance Survey data © Crown Copyright and database rights 2014.

## 6. Availability of the model data

A fence diagram of cross-sections through the model is available from the BGS website.

Other digital data such as surfaces from the model are available for use in GIS and geological modelling software under licence. In addition BGS has also developed the BGS Groundhog application for the delivery of spatial information from the model.

### 6.1. Free data

Automatically generated sections from the model are made available in PDF format for anyone to view and download from the BGS Open Geoscience webpages under the Open Government Licence at <http://www.bgs.ac.uk/opengeoscience/home.html?src=topNav>. The cross-section lines are at 10 km intervals, aligned to the British National Grid and running both north-south and east-west (Fig. 8). The sections are available individually and as the complete fence diagram. The spacing is both adequate for stakeholders to understand what the overall geology is, and the level of geological detail contained in the model.

### 6.2. Licensed data

Geological model data can be supplied in a wide range of generic 2D and 3D formats. Individual surfaces can be supplied as TINS (triangular irregular networks), DXF files for BIM/CAD software and as ASCII grids; and 3D geometries can be supplied for example as ESRI multipatches, or GOCAD<sup>®</sup> shells. The model can also be exported as 3D grids at a user-defined cell spacing. In addition, models can be delivered in a standalone BGS LithoFrame Viewer that allows the user to interact with and perform spatial queries on the model. This viewer is available at: <http://www.bgs.ac.uk/research/ukgeology/nationalGeologicalModel/GB3D.html>.

### 6.3. BGS Groundhog georeports

The London and Thames Valley model is also sufficiently detailed to allow automated prognoses of the general geological conditions that might be expected at a site, along a route, or at a specified depth. Whilst these prognoses can be used to plan investigations, they cannot be used as substitute for the actual site investigations. BGS has developed the BGS Groundhog application for this purpose; it provides clients with bespoke auto-generated borehole logs, cross-sections along specified alignments and horizontal cuts at either a specified level, relative to OD, or beneath the ground surface. Each is accompanied by a map, descriptive text listing the geological units present and a colour legend. An illustration of some of the basic outputs elements is given in Fig. 10 and an image of the report output using the standardised BGS template is included as a [supplementary source](#). These outputs are suitable for stand-alone use and for incorporation into reports and other documents.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.pgeola.2014.09.001>.

## References

- Aldiss, D.A., Newell, A.J., Smith, N.J.P., Woods, M.A., 2006. Geology of the Newbury district – a brief explanation of the geological map. Sheet Explanation of the British Geological Survey. 1:50 000, Sheet 267, Newbury, 34 pp.
- Aldiss, D.T., Black, M.G., Entwisle, D.C., Page, D.P., Terrington, R.L., 2012. Benefits of a 3D geological model for major tunnelling works: an example from Farringdon, east-central London, UK. *Q. J. Eng. Geol. Hydrogeol.* 45, 405–414.
- Aldiss, D.T., 2013. Under-representation of faults on geological maps of the London region: reasons, consequences and solutions. *Proc. Geol. Assoc.* 124, 929–994.
- Aldiss, D.T., Burke, H.F., Chacksfield, B., Bingley, R., Teferle, N., Williams, S., Blackman, D., Burren, R., Press, N., 2014. Geological interpretation of current subsidence and uplift in the London area, UK, as shown by high precision satellite-based surveying. *Proc. Geol. Assoc.* 125, 1–13.
- Banks, V.J., Bricker, S.H., Royle, K.R., Collins, P.E.F., 2014. Anomalous buried hollows in London: development of a hazard susceptibility map. *Q. J. Eng. Geol. Hydrogeol.* (in press).
- Berg, R.C., Mathers, S.J., Kessler, H., Keefer, D.A. (Eds.), 2011. *Synopsis of Current Three-dimensional Geological Mapping and Modeling in Geological Survey Organisations*. Illinois State Geological Survey Circular 578, 92 pp.
- Berry, F.G., 1979. Late Quaternary scour hollows and related features in central England. *Q. J. Eng. Geol.* 12, 9–29.
- Bridge, D.M., Butcher, A., Hough, E., Kessler, H., Lelliott, M., Price, S.J., Reeves, H.J., Tye, A.M., Wildman, G., Brown, S., 2010. Ground conditions in central Manchester and Salford: the use of the 3D geoscientific model as a basis for decision support in the built environment. British Geological Survey Research Report, RR/10/006, Nottingham, UK 88 pp.
- Bridgland, D.R., 1994. Quaternary of the Thames. *Geological Conservation Review Series No. 7*. Chapman and Hall, London 441 pp.
- Burke, H.F., Price, S.J., 2013. Metadata report for the York and Haxby LithoFrame 10-50 model. British Geological Survey Open Report, OR/13/018, Nottingham, UK 10 pp.
- Burke, H.F., Mathers, S.J., Williamson, J.P., Thorpe, S., Ford, J., Terrington, R.L., 2014. The London Basin superficial and bedrock LithoFrame 50 Model. British Geological Survey Open Report, OR/14/029, Nottingham, UK 27 pp.
- Ellison, R.A., 1983. Facies distribution in the Woolwich and Reading Beds of the London basin, England. *Proc. Geol. Assoc.* 94, 311–331.
- Ellison, R.A., Booth, S.J., Strange, P.J., 1993. The British Geological Survey LOCUS Project: a source of high quality geological maps and computer generated 3-D models of London. *Episodes* 16, 383–388.
- Ellison, R.A., Williamson, I.P., 1999. Geology of the Windsor and Bracknell district – a brief explanation of the geological map. Sheet Explanation of the British Geological Survey. 1:50 000, Sheet 269, Windsor, 29 pp.
- Ellison, R.A., Woods, M.A., Allen, D.J., Forster, A., Pharaoh, T.C., King, C., 2004. Geology of London. *Memoir of the British Geological Survey*. Sheets 256 (North London), 257 (Romford), 270 (South London) and 271 (Dartford) (England and Wales).
- Ford, J.R., Burke, H.F., Royle, K.R., Mathers, S.J., 2008. The 3D geology of London and the Thames Gateway: a modern approach to geological surveying and its relevance in the urban environment. In: *Cities and their Underground Environment – 11th European e-conference of International Association for Engineering Geology*, Madrid, Spain, September 2008, pp. 15–19.
- Ford, J.R., Mathers, S.J., Royle, K.R., Aldiss, D.T., Morgan, D.J.R., 2010. Geological 3D modelling: scientific discovery and enhanced understanding of the subsurface, with examples from the UK. *Z. Dtsch. Ges. Geowiss.* 161, 205–218.
- Gakis, A., Salak, P., St John, A., 2014. Geotechnical risk management for sprayed concrete lining tunnels in Farringdon Crossrail Station. p. 324 in *Tunnels for a better life*. In: Negro, A., Cecilio, M.O., Biflinger, W. (Eds.), *Proceedings of the World Tunnel Congress*. Iguassu Falls, Brazil, May 2014, Sao Paulo CBT/ABMS, 392 pp.
- Gibbard, P.L., 1985. *The Pleistocene history of the Middle Thames Valley*. Cambridge University Press, Cambridge 155 pp.
- Gibbard, P.L., 1994. *Pleistocene history of the Lower Thames Valley*. Cambridge University Press, Cambridge 229 pp.
- Gibbard, P.L., 1988. The history of the great north-west European rivers during the past three million years. *Phil. Trans. R. Soc. Lond.* B318, 559–602.
- Kessler, H., Mathers, S.J., 2004. From geological maps to models – finally capturing the geologists' vision. *Geoscientist* 14/10, 4–6.
- Kessler, H., Mathers, S.J., Sobisch, H-G., 2009. The capture and dissemination of integrated 3D geospatial knowledge at the British Geological Survey using GSI3D software and methodology. *Comput. Geosci.* 35, 1311–1321.
- Mathers, S.J., 2012. Model metadata summary report for the Ipswich-Sudbury LithoFrame 10-50 Model. British Geological Survey Open Report, OR/12/080 16 pp.
- Mathers, S.J., 2013. Model metadata report for the Colchester LithoFrame model. British Geological Survey Open Report OR/13/001 13 pp.
- Mathers, S.J., Terrington, R.L., Waters, C.N., Leslie, A.G., 2014. GB3D – a framework for the bedrock geology of Great Britain. *Geosci. Data J.* 1, 30–42, <http://dx.doi.org/10.1002/gdj3.9>.

- Mathers, S.J., Smith, N.J.P., 2000. Geology of the Reading district – a brief explanation of the geological map. Sheet Explanation of the British Geological Survey. 1:50 000, Sheet 268, Reading, 30 pp.
- Mathers, S.J., Zalasiewicz, J.A., 1988. The Red Crag and Norwich Crag formations of southern East Anglia. *Proc. Geol. Assoc.* 99, 261–327.
- Morigi, A.N., Woods, M.A., Reeves, H.J., Smith, N.J.P., Marks, R.J., 2005. Geology of the Beaconsfield district – a brief explanation of the geological map. Sheet Explanation of the British Geological Survey. 1:50 000, Sheet 255, Beaconsfield, 34 pp.
- Royse, K.R., 2010. Combining numerical and cognitive 3D modelling approaches in order to determine the structure of the Chalk in the London Basin. *Comput. Geosci.* 36, 500–511.
- Royse, K.R., Kessler, H., Robins, N.S., Hughes, A.G., Mathers, S.J., 2010. The use of 3D geological models in the development of the conceptual groundwater model. *Z. Dtsch. Ges. Geowiss.* 161, 237–249.
- Royse, K.R., de Freitas, M., Burgess, W.G., Cosgrove, J., Ghail, R.C., Gibbard, P., King, C., Lawrence, U., Mortimore, R.N., Owen, H., Skipper, J., 2012. Geology of London, UK. *Proc. Geol. Assoc.* 123, 22–24.
- Strange, P.J., Booth, S.J., Ellison, R.A., 1998. Development of 'rockhead' computer generated geological models to assist geohazards prediction in London. In: Maund, J.G., Eddleston, M. (Eds.), *Geohazards in Engineering Geology*. Engineering Geology Special Publication 15, pp. 409–414.
- Sumbler, M.G., 1996. *British Regional Geology: London and the Thames Valley*, 4th ed. HMSO, London 173 pp.