The 3D geology of London and the Thames Gateway: a modern approach to geological surveying and its relevance in the urban environment

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ABSTRACT

As a provider of geological advice to industry, academia and the public, the British Geological Survey (BGS) has recognised the need to change the way it presents geoscientific information, resulting in the construction of attributed 3D geological models. The need to deliver 3D modelling solutions is of great importance in urban areas, where geological factors play a major role in supporting ground investigations and sustainable water management studies. The 3D geological model of London and the Thames Gateway occupies an area of approximately 3200 km^2 and extends to a depth of 150 m. It includes a total of 38 units, ranging from Artificial Deposits and Quaternary sediments down to Tertiary and Cretaceous bedrock. The model is built using existing geological surveys, DEMs and extensive borehole and site investigation data. Modelling was carried out using GSI3D (Geological Surveying and Investigation in 3 Dimensions) software. This software and its associated workflow produce a series of gridded volumes of the geological units, constrained at depth by a network of cross-sections constructed by the geologist. The Thames Gateway model was attributed by assigning property values to each geological unit. This has provided a way of visualising the spatial relationships between geological units with differing properties. The model has revealed previously unrecognised geological information. Further benefits of the attributed model include the ability to visualise and appreciate the link between lithology and physical characteristics. Such models will produce the decision support system necessary for the sustainable development and management of today's megacities.

Keywords: 3D-modelling, London, GSI3D

1 INTRODUCTION

Greater London is the biggest Meagacity in the European Union, with a population approaching 14 million. Urban development in the region continues apace, with current regeneration and infrastructure programmes including new rail links, bridges, sewers, the creation of the Thames Gateway Development Area downriver from the city and the construction of the 2012 Olympic site. Since the 19th century, when London underwent rapid expansion, building and infrastructure projects have contributed key information about the geology beneath the city. Building on this accumulated knowledge, geological advice underpins modern construction and engineering projects, and draws attention to potential hazards and impacts in particular with regard to surface and groundwater. Technological advances in the digital age now enable the existing data to be portrayed not only as 2D maps, often only interpretable by geologists, but as attributed 3D models that clearly show rock-relationships to non-geologists. BGS has recently completed the first set of detailed 3D geological models of the shallow subsurface for London and the Thames Gateway.

2 THE GEOLOGY OF THE LONDON AREA

The bedrock geology of the London area covered by the 3D models is part of the London Basin, a NE-SW trending syncline (Figure 1) (Ellison et al., 2004). The London Basin formed in Oligocene to mid-Miocene times, during the main Alpine compressional event that affected southeastern England. The oldest bedrock unit, the Cretaceous Chalk Group, crops out forming a rim around the Basin. The Chalk, which is over 200 m thick, is the region's principal aquifer, famous historically for its artesian flow from wells sunk near the centre of the Basin and its susceptibilty to collapse due to dissolution. Overlying the Chalk, the oldest Paleocene deposit is the Thanet Sand Formation. This Formation consists of a sequence of finegrained glauconitic sands with a basal bed of flint cobbles and boulders derived from the Chalk. The Thanet Sand reaches a maximum thickness of around 40 m in the east of the area but thins rapidly westwards to its limit beneath western London. Above the Thanet Sand lies the Lambeth Group. This lithologically variable group is up to 30 m thick in the area, consisting of variable proportions of sands, silts, clays and gravels. It is characterised by its spectacular colour-mottled clays which were prized for brickmaking.

The overlying Eocene sediments form the Thames Group, which consist of the basal Harwich and an upper London Clay formations. The Harwich Formation consists predominantly of sand and pebble beds up to 10 m thick. The London Clay Formation comprises up to 150 m of grey to blue-grey, bioturbated, silty clay. Higher Eocene sediments of the sandy Bagshot Formation occur as isolated outliers on some of the highest hills in the area, reaching a thickness of around 30 m.

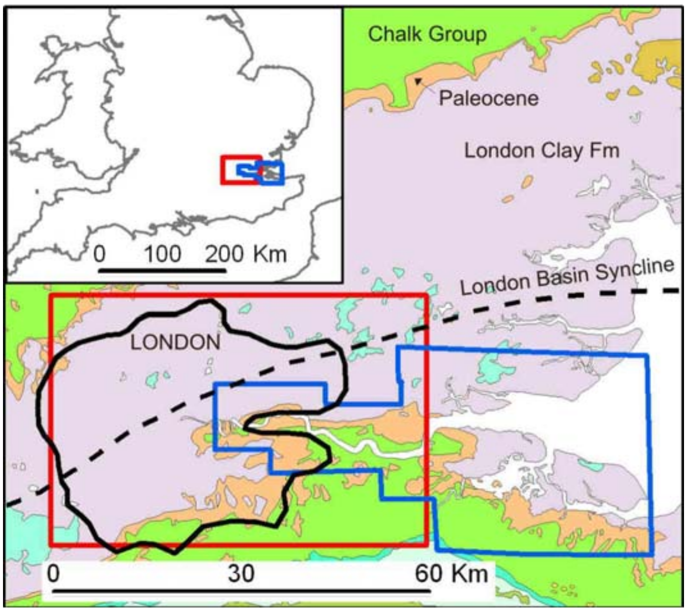

Figure 1. Map summarising bedrock geology of the London Basin and the extent of 3D modelling; London LithoFrame (red) and Thames Gateway (blue). OS Topography ©Crown Copyright. All rights reserved 100017897/2008.

Superficial Quaternary deposits are widely developed in the London area. These deposits include river and intertidal alluvium, peat, brickearth and river terrace deposits associated with the current and previous courses of the River Thames.

Urban development and industrial mineral extraction in the region have resulted in a complex distribution of worked, made and infilled ground, collectively referred to as Artificial Deposits.

The principal engineering geology and environmental factors associated with the geology of the London area are presented in Table 1.

Lithostratigraphic unit	Potential Ground Constraint
Artificial Deposits	▪ Variable excavation and foundation conditions ▪ Groundwater protection issues
Alluvium	▪ Risk of flooding ▪ Variable excavation and foundation conditions ▪ Variable and poor load-bearing capacity
“Brickearth”	▪ Metastable when wet
River Terrace Deposits	▪ Variable excavation and foundation conditions ▪ Highly variable thickness ▪ Potential for “scour hollows”
London Clay Fm.	▪ Ground heave and subsidence ▪ Landslips ▪ Shrink-swell effects
Lambeth Group	▪ Variable excavation and foundation conditions ▪ Running sand ▪ Shrink-swell effects ▪ Local thick flint pebble beds
Thanet Sand Fm.	▪ Hydrological continuity with the Chalk ▪ Running sand
Chalk	▪ Groundwater protection issues ▪ History of over-abstraction ▪ Dissolution cavities and sink holes ▪ Variable excavation and foundation conditions

Table 1 Summary of potential geohazards and ground constraints (modified after Ellison et al., 2004)

3 PREVIOUS SURVEY WORK

The history of geological surveying in the London area began with publication of the first memoir in 1872 (Whitaker, 1872), based on mapping that began in 1861. Early survey work recognised the role of geology in underpinning rapid urban expansion of Victorian London (Culshaw, 2004; Culshaw et al. 2008). These early survey publications contain numerous sections from rail cuttings and accounts of borings and tunnels that illustrate the subsurface geology of the area.

Continued urban growth, including the construction of the London Underground (metro), road and further rail networks demanded up-to-date geological information, and provided the data to support several revised maps, accounts and more recently, 3D modelling work (Strange et al., 1998). The current memoir of the London area (Ellison et al., 2004) describes the 4 mapsheets published in the 1990s for the North London, South London, Romford and Dartford districts. This work provides an increased level of information on the subsurface geology through a range of subcrop maps, structure contour plots and 3D views.

Recent advances in affordable computing power, digital data and software development have allowed geologists to take the next step in understanding and communicating the subsurface geology of the London area: not just as maps but through the construction of detailed 3D geological models.

4 THE MODELLING APPROACH

The BGS's approach to 3D geological modelling of relatively shallow and un-deformed strata, including that of the London area, is described by Kessler and Mathers (2004) and Kessler et al. (in press). This methodology has been successfully employed in a range of research in the UK and overseas (Merritt et al., 2007; Wycisk et al., in press).

The GSI3D method utilises a digital terrain model, geological surface linework and downhole borehole data to enable the geologist to construct regularly spaced, intersecting cross sections. These are combined in a fence diagram which shows the correlation of individual lithostratigraphic units and their lateral extent in the subsurface. Mathematical interpolation between nodes that define the base of each unit produces a solid model comprised of a series of stacked triangulated objects corresponding to each of the geological units present (Figure 2).

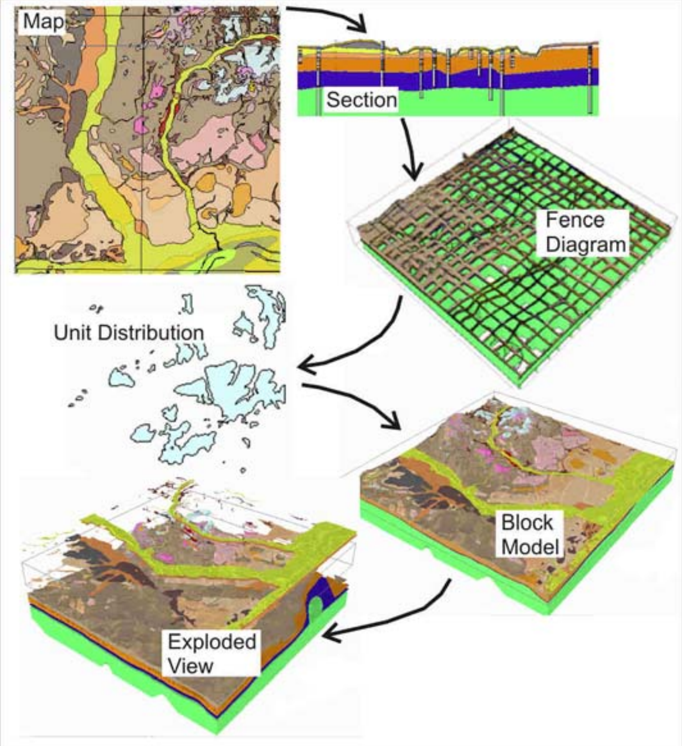

Figure 2. The GSI3D workflow used in the construction of the 3D geological models of London and the Thames Gateway

Geologists interpret their sections based partly on factual information, where the borehole information and correlation is secure, and partly on geological experience - the shape 'looks right'. This 'looks right' element pulls on the modeller's wealth of understanding of geological processes and knowledge gathered over a career in geology.

The process of 3D modelling allows the geological surveyor to collate and consider a far wider range and volume of data than with conventional 2D map construction. Surface and subsurface information can be brought together and visualised from any perspective. This contextually-enhanced view of the data highlights spatial relationships and improves the accuracy of the geological interpretation.

5 MODELLING IN THE LONDON AREA

Modelling in the London area has been completed for a variety of strategic scientific and commissioned projects, each fit for purpose at a range of scales.

The Thames Gateway model (Figure 1) is built from over 4000 boreholes and over 2,300 line-kilometres of north-south and east-west trending cross-sections. The model includes a detailed subdivision of artificial ground, Holocene deposits and selected Bedrock units. The Thames Gateway model is commensurate with geological mapping at a scale of 1:10 000.

A second modelling initiative, the London LithoFrame, extends model coverage of the London area to include Outer London, southwest Essex and northwest Kent (Figure 1). This strategic model is based on over 6,700 line-kilometres of correlated cross-sections. This model provides an equivalent level of detail to 1:50 000 scale mapping and represents the 3D equivalent of the geological map of London (Figure 3).

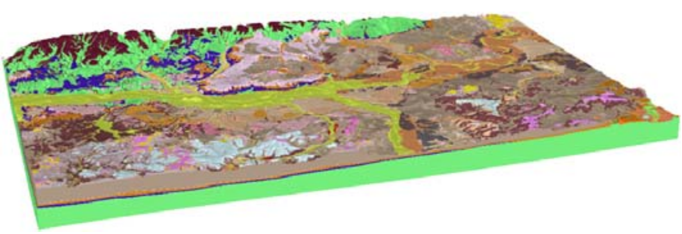

Figure 3. Oblique view of the London LithoFrame model viewed towards the south

The Thames Gateway and London LithoFrame models occupy an area of approximately 3200 km^2. The combined model extends to a depth of 150 m, and represents a total of 38 units. In many parts of the model, borehole data is available in such large quantities that not all records can be used. A review and prioritisation of the available data ensures that the most reliable and representative records are incorporated in the model. Boreholes that are not considered initially can be introduced at a later stage to refine the interpretation.

Further modelling at smaller and larger scale has been completed. These models provide additional information on the deeper structure of the London Basin, and very high levels of detail at specific sites (Royse et al., 2006a). All 3D models in the London area are constructed to integrate seamlessly across scales.

6 LONDON MODELS EXPLORED

GSI3D provides a suite of investigative tools and visualisation modes that allow calculated models to be explored in response to a range of geology-related queries. These tools allow the geological framework and underlying data to be investigated in ways that would be impossible, or require significantly greater effort, to achieve through manual 2D mapping and GIS technology alone.

The spatial definition of surface and concealed extents for each geological unit provides an immediate benefit over conventional 2D mapping that typically represent only the outcrop distribution of each unit. The surface and concealed extent of each unit are presented in both 2D and 3D, allowing the spatial relationship between multiple concealed units to be considered.

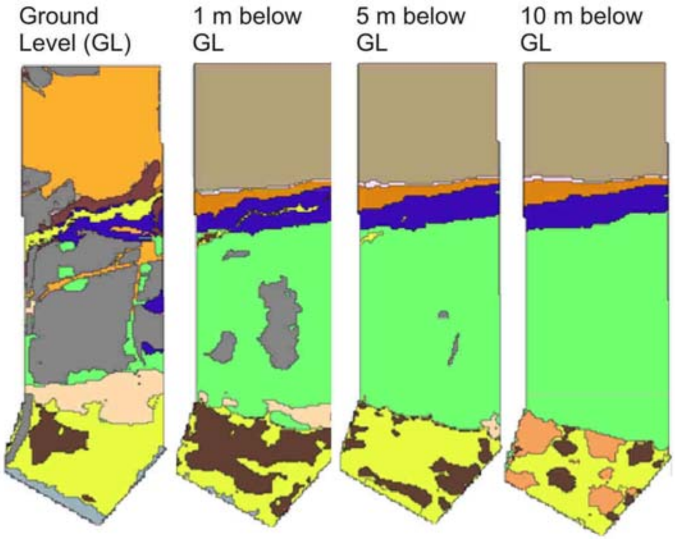

Figure 4. Horizontal depth slices through part of the model showing the subsurface distribution of Artificial Deposits, Superficial Deposits and Bedrock units.

Surfaces defining the tops or bases of units can be readily investigated through contouring, colour-graded shading and 3D visualisation. Similarly, unit thickness can be explored to reveal further detail on the morphology of each unit. In the London area, this approach has resulted in an improved rockhead elevation model and a far greater understanding of the distribution and extent of River Thames Terrace Deposits, and their denudation chronology. 3D modelling of these deposits has revealed scour hollows and their relationship to underlying units.

The geological succession at any point on the model can be visualised using the borehole prognosis tool and reported as a “synthetic log”. The model can be sectioned in any orientation to provide vertical profiles or horizontal profiles (Figure 4). In the London area, “synthetic sections” have been constructed along proposed linear routes to support a range of engineering projects.

Model visualisation in the BGS’s walk-in 3D projection room has encouraged collaborative working and knowledge transfer between groups of geologists. This has resulted in the development of a revised structural framework for the London area: the active stereo capability of the facility has highlighted geometric features in the modelled bedrock surfaces that, together with information from outcrop, can be confidently interpreted as a network of previously unrecognised faulting and folding (Figure 5). This improved structural model will inform the sustainable management of groundwater resources in the area.

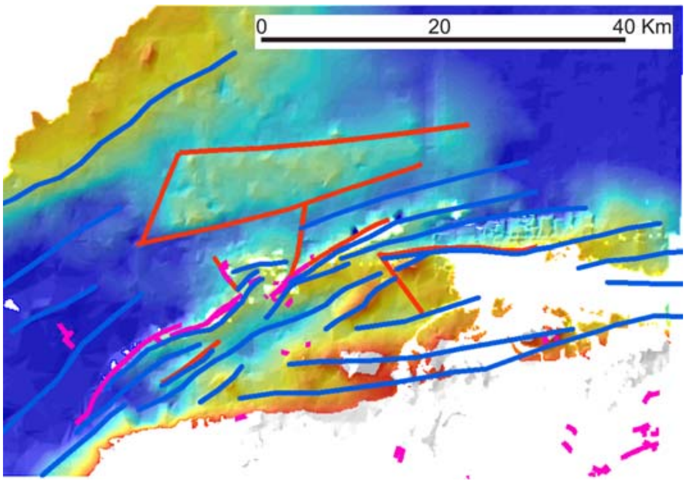

Figure 5. Colour-ramped elevation grid for the modelled top-Chalk surface (+50 to -100 m AOD) in the London area showing the revised structural framework: previously mapped faults (purple), new faults (red) and new fold axes (blue).

Modelling in the London area has highlighted improvements to the published geological map, including modification of the structural relationship, spatial extent, and lithostratigraphic classification of units. Changes specified by the model will feed back to the 2D geological map (DigMapGB) ensuring consistency between 2D and 3D data.

Advanced exploration of the London modelling is facilitated by close integration of GSI3D outputs with 2D and 3D GIS applications, 3D modelling applications and hydrogeological software including Zoom and ModFlow (Kessler et al., 2007).

7 EXTENDED MODEL ATTRIBUTION

The lithostratigraphic model provides a framework into which additional qualitative physical property-based information for each modelled unit can be placed, analysed and reported. The integration of property-based information allows multiple thematic representations of the model to be derived, each addressing specific engineering geology or environmental applications. The investigative tools available to explore the geological framework can be applied to the thematic representations of the model, providing a powerful mechanism for knowledge transfer.

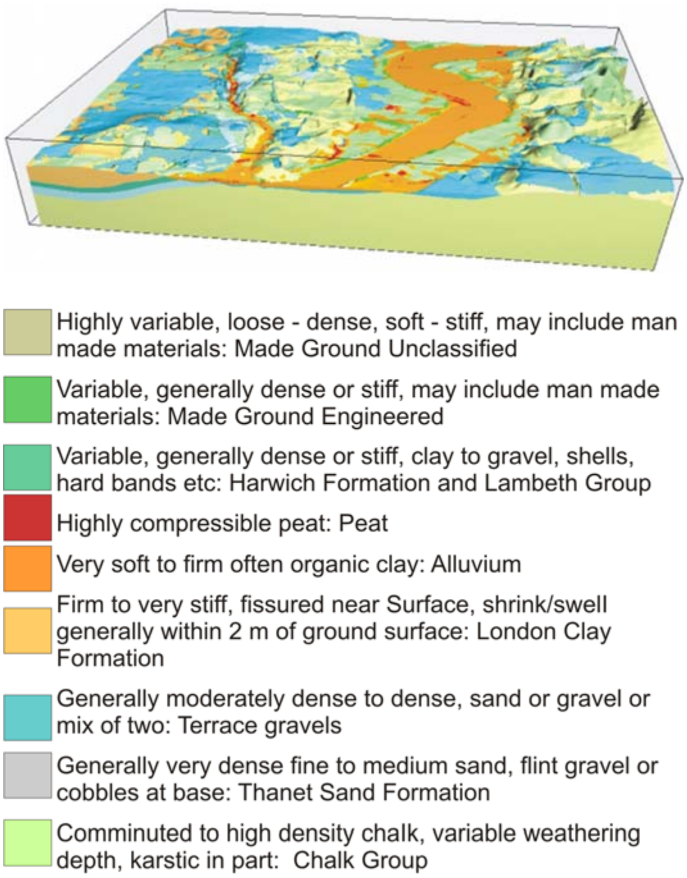

Figure 6. 3D geological model of part of the Thames Gateway showing variation in compressibility. Areas of high compressibility are coloured in orange and red, variable compressibility coloured in light brown to green and areas of low compressibility are in blue to brown (after Royse et al. 2006b).

Bulk attribution of the Thames Gateway model with hydrogeological, engineering and confidence data obtained from over 3200 boreholes, trial pits and geophysical investigations, has provided a decision support tool for a range of end-uses including the tunnelling and construction industry, water authority and developers of ground source heat pumps (Royse et al., 2008 and Royse et al., in press).

Model attribution with engineering properties, including strength or density data offers a predictive tool for rock strength, shrink-swell characteristics and compressibility; key factors in understanding and mitigating the ground constraints encountered in the London area (Figure 6).

Model attribution with hydrogeological properties, including permeability and porosity is used to show the thickness of the unsaturated zone and the likelihood of perched water tables. Significant hydrogeological situations can be identified, including areas where aquifer units are "sealed" from recharge by impermeable cover or exposed for recharge and potential contamination (Figure 7). 3D visualisation of the attributed model reveals parts of the bedrock succession where faulting has juxtaposed discrete aquifer units, resulting in structural hydrological continuity (Figure 8).

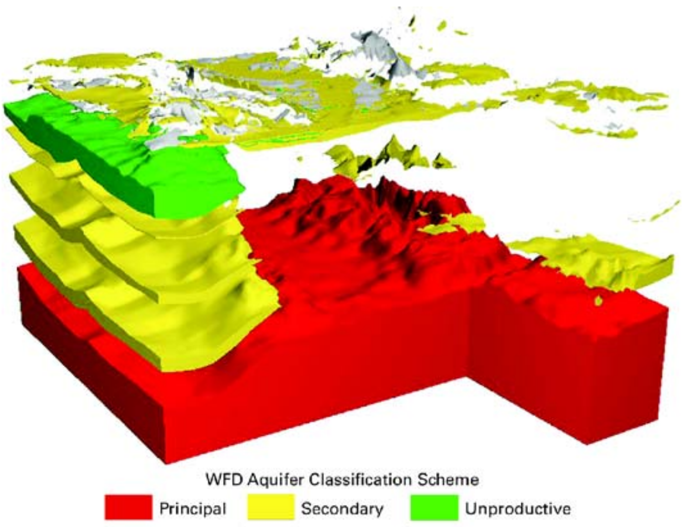

Figure 7. Exploded 3D view of part of the Thames Gateway model attributed and coloured to show relative permeability of the geological succession according to the Water Framework Directive (Royse et al., in press).

3D geological models of the London area are supporting ongoing research into 4D modelling and the reconstruction of the geological evolution of the area and in particular the Quaternary history. Animations and time-series models will provide an improved understanding of depositional environments and sedimentary architecture, and their relationship to ground conditions and hydrogeology in the London area. Further work on property modelling will explore voxel-based attribution as a tool to provide improved control on intra-formational variation.

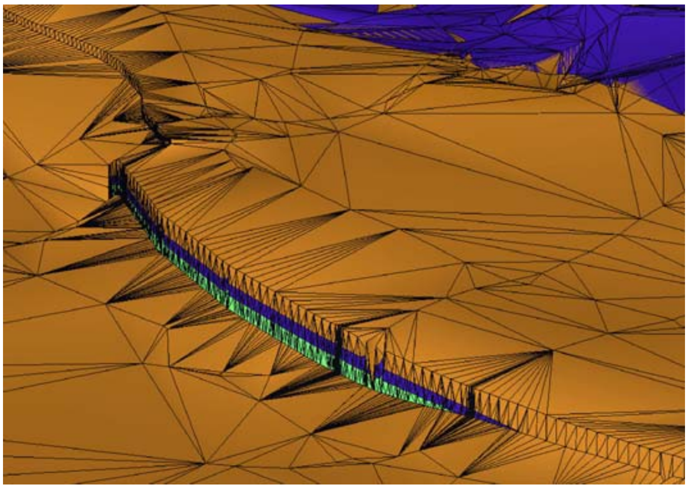

Figure 8. Oblique view of selected bedrock units showing offset along part of the Greenwich Fault and the hydrogeological window to the Chalk Group aquifer (green).

8 CONCLUSIONS

The geological models of London and the Thames Gateway described here represents a significant advance in the BGS's capability to depict geology in 3D. The application of innovative procedures and software for the contextual appraisal of diverse spatial data has resulted in an improved understanding of London's geology, providing a framework for ongoing geoenvironmental research. This modern approach to geological surveying provides an effective means of capturing, enhancing and communicating geology to the public. As a result, the future envisaged by Culshaw (2005), where ground investigations will start by testing the validity of a 'real' geological model, is rapidly becoming a reality.

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REFERENCES

Culshaw, M.G. 2004. The first engineering geological publication in the UK? Quarterly Journal of Engineering Geology and Hydrogeology, 37: 227–231.

Culshaw, M.G. 2005. From concept towards reality: developing the attributed 3D model of the shallow subsurface. Quarterly Journal of Engineering Geology and Hydrogeology, 38: 231-284.

Culshaw, M.G, Reeves, H.J. and Rosenbaum, M.S. 2008. Two hundred years of engineering geology. Quarterly Journal of Engineering Geology & Hydrogeology; 41(2): 137-142.

Ellison, R.A., Woods, M.A., Allen, D.J., Forster, A., Pharaoh, T.C. and King, C. 2004. Geology of London. *Memoir of the British Geological Survey*, Sheets 256 (N. London), 257 (Romford), 270 (S. London) and 271 (Dartford).

Kessler, H and Mathers, S.J. 2004. Maps to Models. Geoscientist, 14(10): 4-6.

Kessler, H, Mathers, S.J., Lelliott, M, Hughes, A and MacDonald, D. 2007. Rigorous 3D geological models as the basis for groundwater modelling. In: Three-dimensional geologic mapping for groundwater applications, Workshop extended abstracts, Denver, Colorado.

Kessler, H, Mathers, S.J., Sobisch, H.G. In press. The capture and dissemination of integrated 3D geospatial knowledge at the British Geological Survey using GSI3D software and methodology. Computers & Geosciences.

Merritt, J.E., Monaghan, A., Entwisle, D., Hughes, A., Campbell, D., and Browne, M. 2007. 3D attributed models for addressing environmental and engineering geoscience problems in areas of urban regeneration – a case study in Glasgow, UK. In: First Break, Special Topic Environmental and Engineering Geoscience, 25, August 2007: 79-84.

Royse, K.R., Entwisle, D., Price, S. and Terrington, R. 2006a. Geoscience solutions for the Thames Gateway. IAEG 2006 Congress Proceedings: 1-7.

Royse, K.R., Entwisle, D., Price, S., Terrington, R. & Venus, J. 2006b. Gateway to Olympic success. Geoscientist, 16(5): 4-10.

Royse, K.R., Reeves, H.J. & Gibson, A.R. 2008. The modelling and visualisation of digital geoscientific data as an aid to land-use planning in the urban environment, an example from the Thames Gateway. In: Communicating Environmental Geoscience (edited by Liverman, D. G. E., Pereira, C. & Marker, B.) Geological Society, London, Special Publication, 305: 89-106

Royse, K.R., Rutter, H.K. and Entwisle, D.C. In press. Property attribution of 3D geological models in the Thames Gateway, London : new ways of visualising geoscientific information. Bulletin of Engineering Geology and the Environment.

Strange P.J, Booth S.J and Ellison R.A. 1998. Development of 'rockhead' computer –generated geological models to assist geohazards prediction in London. In Maund J.G. and Eddleston M. (eds) Geohazards in engineering geology. Geological Society Engineering Geology Special Publication 15: 409-414.

Whitaker, W. 1872. The geology of the London Basin, Part I. The Chalk and the Eocene Beds of the Southern and Western tracts. *Memoir of the British Geological Survey*, England and Wales.

Wycisk, P., Hubert, T., Gossel, W. and Neumann, C. In press. High-resolution 3D spatial modelling of complex geological structures for an environmental risk assessment of abundant mining and industrial mega sites. Computers & Geosciences.