Chapter 25: 3D Geoscience for the UK and Beyond

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Introduction

With over 20 years of development in 3D capability, geological modelling is now becoming the primary tool for geoscience investigation by the British Geological Survey (BGS). 3D modelling underpins a broad range of research activities, and geological models are being developed at all scales from sites, to cities, to the UK landmass and continental shelf using a range of different software tools and methodological approaches.

3D modelling is advancing our understanding of geological systems by allowing us to integrate more diverse data sources, attribute a range of different properties, and assess the limitations of our data and knowledge. Recent advances in volumetric and geostatistical modelling are also enabling new integrated process modelling and supporting pioneering subsurface environmental monitoring initiatives.

The increasing availability of 3D models is transforming the way in which we view the subsurface and creating new opportunities for delivering knowledge to our stakeholders—through development of new resources and services, by enabling new approaches to knowledge exchange and engagement, and by supporting our many international partnerships.

This paper presents an overview of recent geological modelling within the BGS, and highlights critical issues arising from the growing influence of modelling across a range of BGS activities. The rise of modelling is providing many opportunities, but also brings a range of challenges for managing data, keeping pace with the rapid rate of technological change, maintaining geoscience skills, and developing new delivery methods. Making the most of the opportunities that modelling provides is therefore not just the role of the geological modeller, it also requires the wider evolution of geological survey functions.

Organizational Structure and Business Model

The BGS is the UK’s public sector research institute tasked with the development, curation, and communication of geological data, information, and knowledge. Alongside the provision of up-to-date understanding of UK geology for government, industry, and wider UK society, the BGS undertakes geoscience research to address societal challenges in decarbonisation, environmental adaptation, and Earth hazard mitigation both in the UK and globally through international research partnerships (British Geological Survey, 2019).

The BGS is operated under the newly formed body UK Research and Innovation (UKRI), which supports the UK’s research councils and research institutes and provides independent administration of UK research funding. The BGS is overseen by an independent Board on behalf of UKRI and the National Environment Research Council (NERC).

The BGS operates a mixed funding model, with an annual turnover of approximately £50 Million, of which just over 50% is from NERC through our national capability allocation and competitively won NERC research income, and the other half comes from commercial contracts, research grants (e.g. Horizon 2020), and data licensing.

Overview of 3D Modelling Activities

Geological modelling is now used widely across BGS activities as a key tool for applied geoscience research.

Our modelling capability is underpinned by the in-house development of explicit modelling tools (GSI3D and Groundhog® Desktop; e.g. Kessler et al., 2009), and the use of proprietary software such as Petrel E&P™, DecisionSpace® and SKUA-GOCAD™ (e.g. Aldiss et al., 2012; Campbell et al., 2010; Kearsey et al., 2018).

The BGS-developed Groundhog Desktop GSIS (desktop geoscientific information system) is a graphical software tool designed for the display of geological and geospatial information, and the construction of cross-sections through stratigraphic correlations. The software facilitates the collation, display, filtering, and editing of a range of data including borehole data, geological map linework, interpreted cross sections and faults, as well as elevation models and images (including seismic sections).
Groundhog Desktop is being developed to succeed the earlier GSI3D platform.

Over the past 15 years, geological models including fence diagrams of intersecting cross-sections, surface and volumetric models have been developed for many different parts of the UK. Many of the models produced by the BGS are held in the national GeoModel Store, a repository containing c. 160 models, some of which are available for licencing by external users. These models have been produced through centrally funded ‘national-capability’ geoscience programmes, and were developed as part of commercial contract work.

The models developed by the BGS cover different geological settings in the UK and overseas at scales ranging from development sites, transport corridors and urban regions, to sedimentary basins and national coverage. Whilst many models are developed and designed for application to industry, strategic planning and regulation, targeted geological modelling is also undertaken by the BGS to advance geoscience research in areas as diverse as geological processes and structures (e.g., Newell et al., 2018), aquifer systems (e.g., Jackson et al., 2011), and coastal evolution modelling (e.g., Payo et al., 2018). Geological models are also being developed to underpin the new UKGEOS research platform for subsurface environmental monitoring, in which the integration of real-time telemetry data from new subsurface sensor systems will transition 3D models to 4D.

The National Geological Model project has recently been repositioned as the focus of the BGS’s national geoscience programme and will aim to develop surface and volumetric geological models for the UK’s deep and shallow subsurface. These models will provide a new generation of geological resources for the UK and support process and scenario modelling for environmental and energy resource applications. A current project benefiting from early developments in volumetric modelling for the UK is the Hydro-JULES project, a multidisciplinary collaboration to develop the UK ‘water model’ through integration of climate, hydrological, and hydrogeological process models (Hydro-JULES, 2018).

**Resources Allocated to 3D Modelling Activities**

The diversity and ubiquity of geological modelling within the BGS’s research and commercial activities precludes detailed assessment of the resources and staff allocated to 3D modelling tasks. The BGS operates a project-based system where staff work on research activities across a number of programmes, thus some degree of 3D geological modelling capability is increasingly being required of all geoscience staff within the BGS. The development of modelling skills is being encouraged through active training programmes and collaboration between geologists and advanced geological modellers, in addition to targeted recruitment of geological modellers, data scientists, and statisticians. Cross-disciplinary projects are also stimulating innovation in our 3D geological modelling community by linking geophysicists, geologists, petrophysicists, fluid modellers, and data scientists.

The National Geological Model project (NGM) coordinates the UK’s national geological modelling programme. The development of the current UK3D national fence diagram under the NGM (cf. Mathers et al., 2014), was supported financially by national capability funding covering the equivalent of 6 – 7 full time staff with additional commercial income. This funding supported work by a team of c. 10 – 15 regional geologists working part time on the project. Since the completion of the UK3D model in 2016, the national capability funding for the NGM programme has decreased to the equivalent of 2 – 4 full time staff per year. The new NGM programme commencing in 2019 will be predominantly supported as a core national capability task with projected funding equating to c. 3 – 4 full time roles.

Geological modelling will also be a key component of new ‘Regional Corridor’ projects, designed to deliver applied geoscience for key socio-economic investment areas in northeastern England and to enhance groundwater management of the chalk aquifer in the London area.

**Overview of Regional Geological Setting**

Located to the northwest of continental Europe, the UK now lies on the stable passive margin of the North Atlantic Ocean. However, it preserves a complex geological collage including rocks and sediments that range in age from the Archean to the present, and reflect repeated Wilson cycles and a large range of palaeoclimatic and palaeogeographic regimes. There are strong regional contrasts in landscape and geological environment, with Mesozoic and Cenozoic rocks generally exposed at the surface in the south and east of Britain while Precambrian and Palaeozoic rocks are more widely exposed in the north and west (Figure 1). In northern and western Britain and in Ireland multiple cycles of ice sheet development and decay during the Quaternary period conditioned the current landscape through glacial erosion of uplands and the deposition of heterogeneous glacial and glaciomarine deposits of variable thickness both onshore, and across the UK’s continental shelf.

Key areas for geological model development include the Carboniferous basins of northern and eastern Britain (including the continental shelf), and the broader Mesozoic basins of southeastern Britain and the North Sea. The former are characterised by complex sedimentary fill comprising cy-
clastic sequences of sandstone and mudstone with variable quantities of limestone, coal and oil shale, and are economically important for energy and mineral resources. The latter are significant for the extent and quality of major aquifers including the Sherwood Sandstone (Triassic) and Chalk (Cretaceous) that provide groundwater reserves for highly populated areas of southern Britain. Methods for basin modelling, including characterisation of normal and reverse faults, stratigraphic surfaces and volumes using both explicit and implicit methods have been applied widely in these areas at local, regional, and basin scales.

Demands for geological modelling in the upland terrains of southwestern England, central and north Wales, northern England, and Scotland are more limited because of their low population and relatively limited resource potential. However, future applications of geological modelling in these areas, including the development of national coverage models, must accommodate complex structural elements including folding and thrusting, and the diverse igneous intrusions that form key features of these terrains.

The shallow subsurface environment (0 – 200 m depth) includes the bedrock erosion surface, a weathering zone, and overlying glacial and post-glacial sediment deposits. This zone is of particular interest in the development of geological models for urban areas, transport corridors, and catchments (groundwater and surface hydrology). The properties of materials within this zone are typically highly heterogeneous as a result of Cenozoic (particularly Quaternary) environmental processes and the impact of recent anthropogenic activities associated with industrial and urban development. Methods used for modelling the shallow subsurface include the development of explicit fence diagram, surface (and shell) models, and stochastic modelling where sufficient data is available.

The diversity of geological environments within the UK highlight the importance of a robust scientific understanding as an essential basis for geological modelling. Sound geological knowledge and reasoning are critical for the selection of appropriate methodologies, defining model specifications (including the stratigraphic framework used), integrating diverse input data (e.g. assigning the relative weight of different information sources), and model evaluation.

Data Sources

A diverse range of data sources are available for UK geological modelling, including geological maps, onshore and offshore seismic data, borehole and well records, digital terrain models, and remote sensing data. Shallow geophysics and airborne geophysical survey data are also available for parts of the UK (Figure 1).

The BGS’ National Geoscience Data Centre hosts the UK’s national onshore borehole archive, containing over 3 million scanned records. These include water wells, hydrocarbon exploration wells, and BGS stratigraphic boreholes, however records of geotechnical site investigations donated by third-parties comprise the bulk of the dataset. Borehole records available for modelling are thus highly variable in age and quality, and are typically focused in urban areas and along transport corridors (Figure 1). Digitisation of legacy borehole records is undertaken largely on an ad hoc basis through BGS research activities, although some systematic programmes for targeted borehole coding have been undertaken. The BGS currently holds digitised records for over a million onshore boreholes. Many of these are open access records, and increasing numbers of restricted-access legacy records are being made open access as time-limited confidentiality clauses expire.

Seismic data (2D and 3D) and deep well data, including downhole geophysical logs, are available for the UK landmass and continental shelf from the UK’s Oil and Gas Authority (the OGA). Offshore data in particular are typically high quality, but have historically been subject to commercial restrictions on usage. However, released offshore well and seismic data is increasingly being made openly available via the OGA’s Open Data Portal. Onshore seismic data and deep wells are available for many of the UK’s major Carboniferous and Permo-Triassic basins, although the distribution and quality is highly variable. Data coverage within pre-Carboniferous terrains in Scotland, Wales, and southwestern England is limited (Figure 1).

Detailed mine plan data from historical coal extraction, is available for regions in Central Scotland, northern England, and South Wales. Mine plans provide valuable sources of structural data, but are time-consuming and costly to digitise. Long-term

Figure 1. Overview maps of the UK: A) Geology of the UK landmass and continental shelf derived from the BGS onshore 1:625,000 bedrock geology map and 1:250,000 marine bedrock geology map; B) UK gridded population density for areas classed as urban and suburban (Reis et al., 2017; contains National Statistics data © Crown copyright and database rights) and major transport corridors; C) The distribution of BGS-held onshore digital borehole records and publically released offshore wells supplied by the UK Oil and Gas Authority (Open Data), overlain by the distribution of geological models currently held by BGS; D) The distribution of released geophysical datasets for the UK landmass and continental shelf, includes UK Oil and Gas Authority Open Data. The UK coastline is shown by the blue outline in all images. Contains Ordnance Survey Data © Crown copyright and database rights 2018. Ordnance Survey Licence No. 100021290. Created using ArcGIS © ESRI. All rights reserved.
investment by the BGS in mine plan digitisation in Central Scotland has yielded a key dataset for geological modelling in this region, which is helping to support new research into geothermal potential from mine-waters (Monaghan et al., 2017).

A range of Digital Terrain Models (DTMs) derived from LIDAR, radar, and photogrammetry are available for the UK at resolutions of 1 – 5 m (e.g., NextMap and Bluesky). Remote sensing data are also available at a range of scales for most of the UK, although their use may be limited by cloud cover and vegetation/urban effects. Increasingly, these datasets are enhancing our capability in modelling near-surface geological systems through the use of geomorphometric and data analytical techniques. Similarly, bathymetric data such as DigBath and GEBCO, together with offshore seismic data are enabling modelling of the near-surface geology offshore with relevance to windfarm development and large-scale modelling/mapping of the UK’s continental shelf (e.g., rock at sea bed).

The capture of shallow geophysical data using shallow and passive seismic, electrical resistivity tomography, and ground penetrating radar is a growing focus for new data collection. Although limited in coverage, these data are increasingly being integrated into modelling workflows as constraining datasets for targeted local models, and will be used as test datasets for validation of regional and national-scale models.

High-resolution airborne geophysical data is also available for parts of the UK. The value of these data for advancing geological understanding and generating new opportunities for mineral exploration is highlighted by the TELLUS project in Northern Ireland (Young and Donald, 2013; Figure 1), where geological maps and models, including the UK3D fence diagram, are being updated through interpretation of new high-resolution airborne gravity and magnetic datasets (e.g., Leslie et al., 2013).

3D Modelling Approach

The complex geology of the UK provides both opportunities and challenges for the development and application of geological models. A range of different approaches are employed within BGS geological modelling activities, with methods selected according to the research need, available data sources, and geological context. In some cases different modelling methods are combined within integrated workflows.

The in-house GS13D and Groundhog Desktop software tools are based on an explicit modelling methodology, using fence-diagrams constructed by geologists to constrain the 3D structures of the subsurface and interpolation algorithms to project surfaces (e.g., Kessler et al., 2009). The fence-diagram approach is most effective for the shallow subsurface where borehole and digital mapping data comprise the main data sources. It is also valuable for regions where data is sparse or the distribution is highly variable. However, the ability of these tools to calculate faulted structures is limited.

Explicit modelling of faulted bedrock (surfaces and structures) in more complex onshore structural terranes is typically undertaken using GOCAD, which allows integration of data from a range of sources including borehole, mine plan, seismic data, and digital map information (e.g., Gillespie et al., 2013; Kearsey et al., 2018; Monaghan, 2014). Explicit modelling approaches using either GS13D/ Groundhog Desktop or GOCAD, or indeed both, are also commonly employed by the BGS in commercial projects due to well-defined explicit modelling workflows. Geological modelling for ‘deep’ geology utilising seismic data in both onshore and offshore areas is undertaken using the industry standard software Kingdom™ and Petrel, with previous usage of DecisionSpace, GeoGraphix® and Vulcan™.

Implicit and geostatistical modelling approaches are also being developed through targeted research projects. Geostatistical (stochastic) modelling of the central Glasgow area, using GOCAD in conjunction with additional geostatistical tools, has been trialled as an approach for modelling heterogeneous Quaternary deposits in the shallow surface using a large borehole dataset (Figure 2; Bianchi et al., 2015; Kearsey et al., 2015; Williams et al., 2018). Implicit modelling using SKUA-GOCAD has also been used to develop regional, property-attributed models (Newell, 2018; Newell et al., 2018) and in the construction of a prototype national-scale gridded bedrock model for the UK designed for advanced groundwater modelling applications.

Current trends in geological modelling innovation within the BGS are seeing increased integration of geophysical data into 3D geological modelling methods, growing use of implicit methodologies, and convergence of geostatistics and data analytical methods with geological modelling, particularly in the characterisation of shallow subsurface systems.

Clients

Bespoke model development for commercial clients in the UK and overseas represents a substantial component of BGS modelling activities. Primary commercial clients for targeted or bespoke modelling in the BGS include the Environment Agency (England), and companies in the construction and geotechnical sectors.

The BGS has developed strong relationships with a range of clients and stakeholders in planning, construction and infrastructure development, and has delivered geological models to in-

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form development projects. Recent examples include the award-winning Farringdon Station project (Aldiss et al., 2012), modelling the HS2 rail corridor for Rayleigh Wave Assessment (e.g., Gunn et al., 2015), and geological models to inform surface and subsurface infrastructure development in Singapore (Building and Construction Agency; Kearsey et al., 2018) and the United Arab Emirates (e.g., Ministry of Energy (Abu Dhabi); Farrant et al., 2018). In the example of the Farringdon Station project, undertaken for the Dr Sauer Group and

Figure 2. Examples of geological models produced by the BGS: a) Groundwater flow attributed geostatistical model (based on (b) adapted after Williams et al., 2018); b) Urban geostatistical model of superficial deposits for central Glasgow (adapted after Kearsey et al., 2018); c) City-region superficial deposits model of the Glasgow conurbation; d) Catchment-scale superficial deposits model of the Clyde catchment; e) Site-scale bedrock model for Farringdon Station, central London; f) Regional bedrock model for the Glasgow area; g) Basin-scale model showing the base of the Chalk (two-way travel time) in the Wessex Basin (southern UK).
CrossRail, geological model development was iterated in real-time during the construction phase of a new underground station in the city of London. Through efficient production of pertinent geological information and data flow, and strong partnership working between the BGS and the clients, the evolving geological model informed decision making during the construction process, resulting in reduced construction cost and ahead-of-schedule project delivery (Aldiss et al., 2012; Gakis et al., 2016).

Geological modelling is also undertaken by the BGS to support the UK’s national and local government, and regulatory organisations. Commissioned urban, catchment and aquifer models developed by the BGS for the Environment Agency (England) are used to understand aquifer systems, and inform environmental regulation (e.g., Whitbread et al., 2013). Basin models have also been developed by the BGS as part of a series of shale gas resource assessments commissioned by the UK’s Oil and Gas Authority (OGA) (e.g., Greenhalgh, 2016; Monaghan, 2014).

Geological modelling undertaken through the BGS’ national-capability Regional Geology Programmes, particularly the development of urban-region models, have been important in supporting and stimulating engagement with stakeholders through associated knowledge-exchange fellowships and the development of the ASK (Accessing Subsurface Knowledge) Network. The ASK Network is a knowledge-exchange consortium linking the BGS with a range of geoscience actors in industry and academia, including water companies, construction and geotechnical firms, environmental regulators, and universities. It enables dialogue over the use and applications of geological models and has also helped to promote new digital data sharing initiatives and standards for onshore borehole data in the UK (Bonsor et al., 2013). Originally established in Glasgow, the network has now extended to Wales and Northern Ireland, and is linked to a number of knowledge sharing networks in England. The development of the ASK Network has aligned with the SubUrban COST programme, a wider European collaboration focused on enhancing geoscience data sharing, application, and integration within policy and decision making at city and regional levels (e.g., van der Meulen et al., 2016).

The BGS delivers a range of publically-accessible resources and services from our national-capability funded 3D geological models and selected commissioned models. These include open data access to our national-scale bedrock model UK3D, open-access models, and associated documentation designed for use in education, and licenced model data for selected regional models (e.g., London). The BGS geological models at a range of scales are also important in supporting the wider UK research sector through collaborations such as the NERC-funded Hydro-JULES project (Hydro-JULES, 2018), and the development of the UKGEOS research infrastructure for energy systems and applied environmental monitoring (e.g., Monaghan et al., 2018).

Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

The initial development of the UK’s national-scale fence diagram was undertaken by the BGS to provide a coherent national 3D understanding to inform groundwater management by the Environment Agency, culminating in the release of “GB3D” in 2012 (Mathers et al., 2014). The GB3D model has been used to assess the distribution of key UK aquifers (Figure 3), and their spatial proximity to geological units that may host potential shale-gas resources (Bloomfield et al., 2014).

During a second phase of development, the GB3D model was ‘densified’ to increase the number of sections, and extended to include Northern Ireland and offshore areas up to 20 km from the coast, leading to the release of “UK3D” in 2015. This model upgrade was prompted by a need for full UK coverage and offshore extension of the sections to inform the National Geological Screening process undertaken by Radioactive Waste Management Limited (RWM Ltd.). This screening process represents a major UK research activity commissioned by the UK Government to identify potential areas that may be geologically suitable for hosting a geological disposal facility for radioactive waste. The UK3D model has formed a key input dataset for the screening’s analysis of the distribution of rock types of interest and tectonic structure (Radioactive Waste Management Ltd., 2016).

The UK3D model is also available to the public as an open data resource via the BGS website, providing a coherent overview of the major structural and stratigraphic elements of the UK geological system. To enhance the delivery of 3D model data for non-specialist users, a new set of Regional Geological Visualisation Models (GV Models), has been developed from UK3D. These GV Models, for 14 regions of England, Wales and Northern Ireland, are constructed in a 3D pdf format and were released as open-access resources in January 2019. The models are designed to encourage user interaction with 3D data and provide essential contextual information for understanding the geological system and interpreting the model (Whitbread and Ritchie, 2018). The availability of these tools will also facilitate stakeholder engagement and consultation activities undertaken by the BGS and by external parties such as RWM Ltd.
Current Challenges

Advances in modelling capability are creating a wealth of new opportunities across BGS research, commercial, and national capability programmes. The growth of modelling, coupled with a move towards more diverse property attribution, is increasing demand for high-quality digital data. In the BGS the two main pathways for increasing digital data availability are the digitisation of legacy datasets and investment in new data acquisition.

Current BGS modelling activities depend heavily on datasets developed through long-term (>20 years) investment in digitisation of analogue data assets, including borehole records, mine plans, and geophysical interpretations (e.g., Kearsey et al., 2018). In order to continue to increase model resolution and reduce uncertainty, advances in data quality and methods for integration of diverse data sets are required. To enhance the quality of data available for modelling, methods for using machine learning to select high-quality data, and to recognise patterns within datasets of differing qualities, are being trialled. For example, the former approach is being used in selecting borehole records for development of a new version of the UK’s Superficial Thickness model (equivalent to depth-to-bedrock).

Developments in “text mining” are now making a wealth of textual (narrative) information available for 2D interrogation and semantic analysis. The BGS is engaged with initiatives such as GeoDeepDive, Geobiodiversity Database (GBDB), and Loop in which knowledge extraction from un-
structured resources supports wider academic research efforts. Harnessing the potential of knowledge extraction and resource linkages to inform geological interpretation in 3D modelling workflows and enrich model delivery is an important short to medium-term innovation challenge for the BGS.

New data capture is increasingly predicated on the need to validate and test geological models. Recent years have seen a dramatic increase in the BGS capture of shallow geophysical data such as passive seismic, ground penetrating radar, and tomography, particularly for constraining and validating shallow subsurface models. This is requiring ongoing development of relevant skills and expertise amongst BGS geoscientists and modellers.

The use of increasingly rich data sources, not all of them quantitative, brings a range of challenges for understanding the uncertainty of geological models. Improving the quantification of uncertainty is widely recognised as a key requirement for the geological modelling community, and is a vibrant area of current research. Arguably, the greatest value for uncertainty information is in helping to direct and prioritise new data collection. Within the BGS, a significant impact of improvements in quantifying uncertainty would be to stimulate new programmes of data capture potentially including mapping, geophysical surveys, and borehole drilling.

Despite much dialogue within the research community, the value of quantitative uncertainty information for many of our stakeholders remains less clear. Dialogue with clients and model users over the value of uncertainty metrics, and relevance of the language used to discuss them, is needed to better understand how we can effectively communicate the limitations of a model’s interpretation as relevant to the user’s needs.

The number and diversity of geological models being generated through BGS research and commercial activities poses a significant challenge for the management of geological models as a UK resource. Model design is influenced by a number of factors, including the geological context, the nature of the available data, and the intended use. Models must be optimised to be of value for research and decision making, and as such, models intended for investigation of, for example, the behaviour and impact of potential energy technologies, radioactive waste disposal, or aquifer system characterisation, may differ in their scope, scale, and the stratigraphy or properties that are represented. Thus, in addition to practical implications for data management and maintenance (i.e., versioning) of models, the question of appropriate contexts for model reuse is also significant. As a recent UK government review of computational modelling notes: “Modellers need to be guided by a clear articulation of the model’s analysis, and a model designed for one purpose may not always be suitable for another” (Government Office for Science, 2018). Our model management approaches must evolve to reflect the dynamic world of modelling at the BGS, establishing robust decision making processes, and ensuring appropriate information capture related to model design, geological content, and limitations.

Lessons Learned

Digital data capture from historic records, although time-intensive and expensive, has been critical for unlocking the power of modelling technology to transform our understanding of the UK’s subsurface. Alongside long-term investment in digitisation of analogue records, the BGS has developed a fully digital data management workflow - from supply to delivery, including a digital records management system, and a new UK digital data deposit portal.

However, creating our digital data infrastructure is only part of the story. Ensuring our future modelling capability relies on sustained data supply from industry, including the geotechnical/construction, energy, and water sectors. To secure future supply and encourage digital data flow, the BGS has developed new consortium-based approaches for stakeholder engagement (including the ASK network), encouraged the pioneering use of contractual agreements to embed digital data standards within industry (e.g., Whitbread et al., 2016), and worked to develop innovative partnerships with industry to facilitate digital data sharing (e.g., Dig to Share). The digital revolution in geoscience does not just mean a change to the practise of geological research – it also requires the geological survey to encourage and facilitate behavioural change across industry.

Since the initiation of geological modelling programmes at the BGS, the development of modelling capability has gone hand-in-hand with investment in stakeholder dialogue and knowledge exchange. As well as ensuring that our modelling programme delivers quality geoscience and value for stakeholders, this partnership focus has increased commercial interest in our modelling ‘services’ and encouraged commissioned work. These commissioned programmes have provided a critical stimulus in the development of our modelling capability, driving innovation in software design, modelling approaches, property attribution, and delivery methods and formats. Thus, working closely with stakeholders and engaging in constructive dialogue has been fundamental for simulating both demand and innovation in the BGS’s 3D geoscience.

Geological models have significant value as communication tools, providing 3D visualisations of the structures and systems of the subsurface, however delivery of 3D-format geoscience data to users is not
straightforward. In addition to delivering data grids and Shapefiles, for example for integration within Building Information Management (BIM) workflows, a range of interactive visualisation tools for 3D data have been developed, including 3D pdfs, interactive viewers and web-based applications, and integration within Geovisionary software and Minecraft (Figure 4). These methods enable visualisation of 3D data and have varying degrees of interactive capability. The development of the 3D pdf has proved to be a valuable tool for communication of 3D geology with a wide range of users including the general public (e.g., Whitbread and Ritchie, 2018), as well as education and industrial sectors. The value of the 3D pdf is enhanced by the ability to integrate important contextual information about the model content, data inputs and limitations, directly within the delivery format. Developed through collaboration between geologists, geological modellers, and cartographers, the success of the 3D pdf delivery format is rooted in the attention paid to communicating the rich scientific content, and to the crafting of a user-orientated design.

Next Steps

From 2019, the BGS will be implementing a new Science Strategy, providing renewed focus for the UK’s regional and national geoscience programmes. Our national programme will focus on the development of a new generation of volumetric models for the UK, including the construction of a UK onshore-offshore gridded bedrock model, and new property-attributed models for key structures of the shallow subsurface (e.g., the bedrock erosion surface). The national bedrock model will involve the construction of a 3D structural ‘basins

Figure 4. Styles and formats for delivery of BGS models: a) the 3D pdf format illustrated by the Assynt Culmination model – cross-sections and the geological map are displayed in a ‘block’ format with modelled thrust planes (orange and green surfaces) projected above ground; b) Grids for various modelling and visualisation applications, here displayed in ArcScene - the upper surface is the UK rockhead model (low elevation is pale green, high elevation is brown to white), the lower surface is the superficial thickness model (thin deposits are pale blue, thick are pink) – note the surfaces have been vertically offset for display purposes (developed using NEXTMap Britain elevation data from Intermap Technologies); c) The BGS-developed Lithoframe Viewer is an example of 3D model viewer applications – this image shows part of the superficial deposits model for the city of Glasgow (a glacial till unit is blue, a glaciofluvial unit is orange, and a glaciolacustrine unit is green), d) 3D visualisation software and applications, illustrated by a Minecraft build of the Ingleborough model (model depth is c. 1 km). Contains data from Minecraft © Mojang 2009-2019. Images a) and b) created using ArcGIS © ESRI. All rights reserved.
and terranes’ framework for the UK landmass and continental shelf as part of a 3D digital research infrastructure. These models will support the development of new geological information resources, underpin new applied research such as integrated climate-groundwater-surface water modelling and energy resource assessments, and provide a platform for the development of predictive (4D) ‘reservoir engineering’ type modelling approaches.

Geological modelling activities will also form core elements of our regional work programmes designed to advance our understanding of the influence of heterogeneous ground conditions on groundwater flow; to test the behaviour and impact of potential energy technologies such as underground deep thermal storage, geothermal systems performance, and hydrogen storage in porous media; and to deliver 3D characterisation of ground conditions to inform infrastructure development. The pioneering UK Geoenergy Observatories project (UKGEOS) to monitor environmental change in the subsurface environment will also supply new telemetry data to transition site-scale 3D geological models into 4D sub-surface monitoring platforms.

The significance of computational modelling for informing strategic planning and policy in fields as diverse as health, infrastructure, manufacturing, and economics, has been recognised in a recent UK Government review (Government Office for Science, 2018). With critical relevance for energy, water, mineral resources, waste disposal, and infrastructure development, geoscience plays an important role in the UK’s future socio-economic development. To ensure the impact of BGS geoscience is not just felt in the spheres of research, environmental regulation, and industry, but reaches critical areas of strategic planning and policy in Government, our geological modelling must progress from 3D characterisation towards the delivery of advanced subsurface environmental process and scenario modelling. Investment in innovative 4D environmental monitoring and development of predictive modelling capabilities will ensure that the BGS geoscience delivers for decision makers in the UK, and for our global partners.

References


