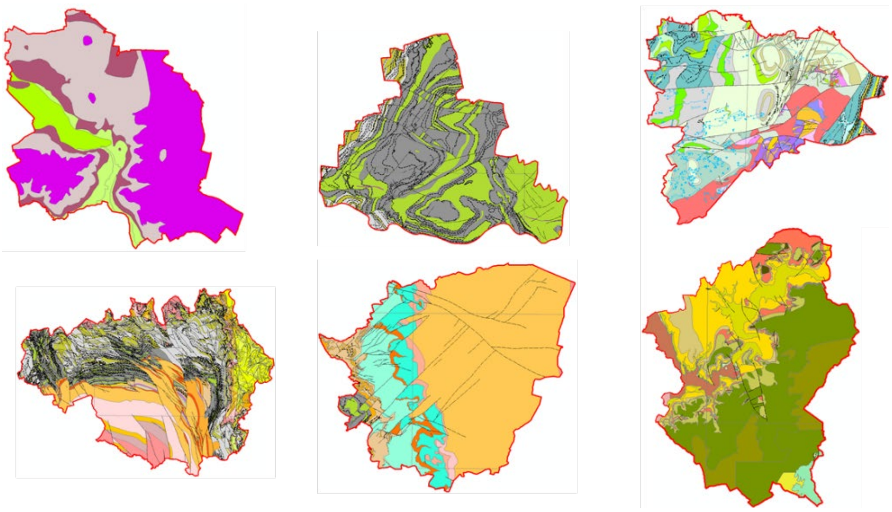
Urban Geoscience Report - Capacity for 3D urban modelling

Environmental, Change, Adaptation & Resilience Programme

Open Report OR/22/043



BRITISH GEOLOGICAL SURVEY

ENVIRONMENTAL, CHANGE, ADAPTATION & RESILIENCE PROGRAMME

OPEN REPORT OR/22/043

Urban Geoscience Report - Capacity for 3D urban modelling

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Editor

K. Whitbread

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Front cover

Bedrock geologies under (top row right to left), Ipswich, Newcastle, Edinburgh, (bottom row right to left) Manchester, Doncaster, Milton Keynes

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Foreword

This report is published by the British Geological Survey Urban Geoscience Team as part of a series of reports to assess current opportunities and challenges in providing geological data, information, and knowledge to inform urban planning policy and sustainable development. The reports focus on the value of geological data and the role of technology in characterising and visualising the shallow subsurface, and how this has evolved in response to stakeholder needs. They also provide recommendations for how BGS data and science should develop to respond to future demands of our urban geoscience stakeholders.

The reports in this series are as follows:

- Urban Geoscience Report - The value of geoscience data, information and knowledge for transport and linear infrastructure projects OR/21/065
- Urban Geoscience Report - Capacity for 3D urban modelling OR/22/043
- Urban Geoscience Report - Geotechnical and engineering geological data and information for urban development at BGS OR/22/049.

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Summary

This report considers opportunities for future 3D urban geology modelling at the BGS. A total of 42 towns and cities in Great Britain were considered in this study, selected based on expected growth areas, e.g. Leeds, Oxford, and/or regionally important urban centres e.g. London, Glasgow. The selected areas also include 13 ‘Cohort 1’ towns identified by the UK Governments Towns Fund, such as Blackpool and Middlesbrough. The review reflects on recent and current 3D urban modelling approaches; considers the nature and complexity of the geology of British towns and cities; evaluates the availability of geological data for 3D modelling and suitable 3D modelling software; and highlights priority areas for innovation. It concludes by providing a series of recommendations for urban geology modelling.

1 Introduction

BGS is considered to be a world leader in urban 3D geological modelling. This reputation was largely developed through the Glasgow and London cross cutting projects and led to follow-up high profile international 3D modelling-focused projects in Europe (Horizon 2020 COST Sub-Urban Action), the Middle East (Abu Dhabi) and Asia (Singapore, ODA-RP2). The impact of the BGS urban geoscience and 3D urban modelling programme in Europe-Asia, as captured for the BGS Evaluation 2021 is described in Box 1 below. Urban 3D geological modelling is distinct from those geological models created to aid Geothermal, Groundwater, Carbon Capture and Storage, Radioactive Waste deposal and conventional and unconventional hydrocarbons because it focuses on shallower depths, typically the top 50m (Figure 1).

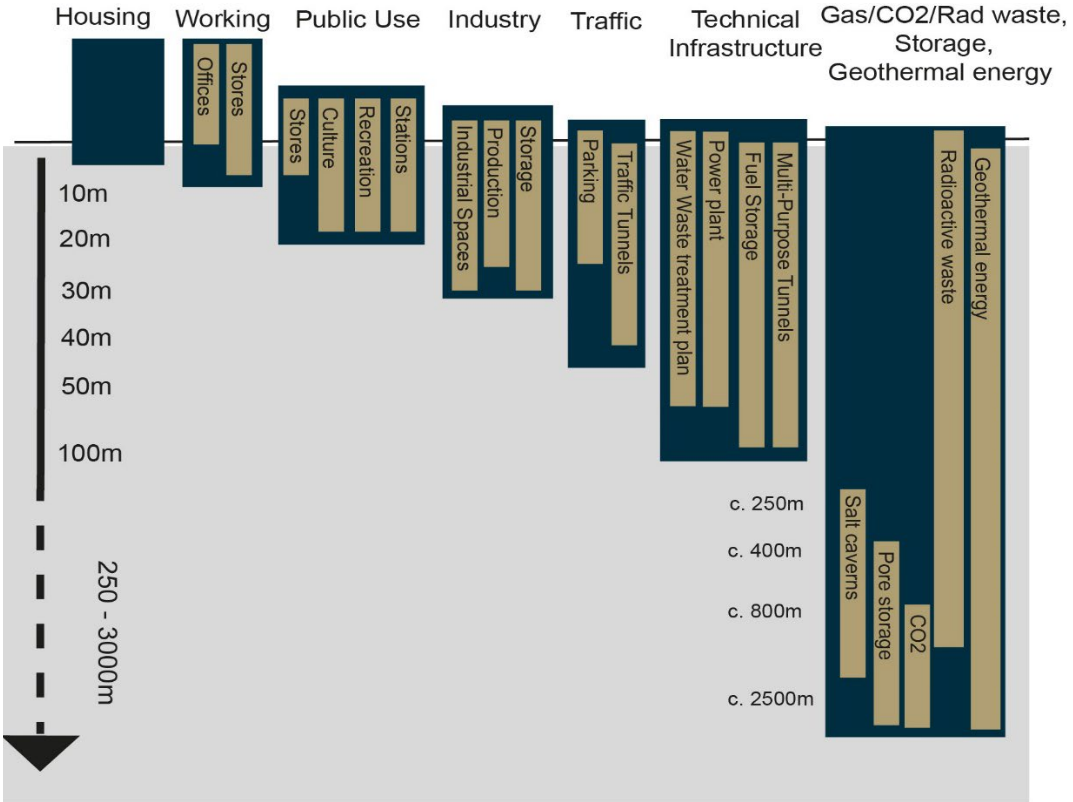


Figure 1 Depth ranges of underground activities (adapted from Evans *et al.* 2009)

Urban 3D geological modelling forms a major output for geological surveys across Europe including (Source EuroGeosurveys Urban Expert Group and Schokker *et al.*2017);

- Norway
- Sweden
- Denmark
- Netherlands
- Ireland
- Finland
- France
- Czech Republic
- Poland
- Spain
- Germany
- Italy
- Belgium
- Slovenia
- Austria

Three-dimensional geological models characterise the changes in depth and spatial distribution of rocks and sediments in the subsurface, providing sophisticated tools for enhanced geological understanding. These models are increasingly at the core of decision making and support advanced analysis for ground conditions, groundwater systems, geothermal assessments and subsurface storage. A review of the economic case for the use of 3D geological models to characterise subsurface conditions is provided by Gates *et al.* (2021). They note the following benefits of 3D geological modelling for infrastructure projects:

- Early-identification of ground conditions, providing opportunities for risk reduction, preparation of competitive bids with reduced optimism bias, and more accurate Geotechnical Baseline Reports.
- Development of a shared digital conceptual ground model to maximise knowledge transfer between different groups of professionals.
- Identification of data-poor areas allowing more targeted design of ground investigation borehole drilling and sampling and reduced uncertainty in ground conditions. A 10% reduction in borehole drilling estimated from existing projects (Bricker *et al.* 2022).
- Near-real time updates to the conceptual ground model following ground investigation, and quick assessment of ground conditions for the design of additional or relocated drilling.
- Improved selection of construction methods, tool selection, earthworks planning and infrastructure design.

Urban 3D geological modelling was at its peak in BGS in the early 2010s. At this time, BGS was at the forefront of digitalisation within the international geoscience community and a leader in the development and strategic deployment of 3D modelling technologies. Aligned to this, National Capability (NC) funding was invested in integrated science research via the Glasgow and London Urban cross-cutting projects, which provided test-beds to apply 3D geological frameworks to real-life urban challenges (Mathers *et al.* 2012; Kearsey *et al.* 2019). However, since the Geology and Regional Geophysics department was disbanded in 2017, the cessation of the urban cross-cutting projects, and sustained reductions in funding for geological characterisation activities have more than halved the number of models created under strategic National Capability programmes.

Current BGS onshore 3D modelling activity in the near sub-surface is largely responsive, with models created as part of commercial and co-funded projects. The Environment Agency (EA) is currently the largest commissioner of BGS 3D geological models, with a number of ongoing mapping and modelling projects progressing under the EA Framework Agreement. BGS geological models are being used by the EA to inform updates to their regional groundwater models, with geological model outputs providing key resources for the hydrogeological characterisation of the bedrock and superficial deposits. There is also an ongoing mapping and modelling programme to provide the EA with geological understanding to support the management of chalk stream catchments in southern England.

Geoscience for sustainable cities. BGS led the EU COST Action Sub-Urban (2013-2017), which brought geological surveys together with city authorities from across > 30 countries in Europe to explore sustainable use and management of the urban subsurface in 3D, and to ensure that the right type of information was supplied to decision-makers at the right time. This network continues in the form of the EuroGeoSurveys Urban Geology Expert Group, for which BGS is the current Chair. These principles were applied first in Singapore, where BGS delivered national geological maps and 3D models for the Building and Construction Authority to support urban planning and underground development. Based on this work, BGS led the development of a new geological framework for Singapore, which is described in a practitioner's guide and has been communicated through a series of workshops. Use of the new (International Commission on Stratigraphy (ICS)-compliant) framework will become national policy for the civil engineering industry in Singapore from 2022.

Building on work in Singapore, BGS has developed urban geoscience research and capacity-building more widely in Southeast Asia, notably with the geological surveys or equivalent organisations of South Korea, Vietnam and Malaysia. These geological surveys are now building their own urban geology research programmes, with urban geology forming part of the organisational strategies for the first time. The General Department of Geology and Minerals of Vietnam has a formalised agreement with the Hanoi City Municipality around a sustainable smart city development project. In Malaysia, BGS work with the Department of Minerals and Geoscience (JMG) has led to the delivery of a borehole database and data entry system, so that data from ground investigations can be held in a consistent digital form. The JMG has now proposed an amendment to the Malaysian Geological Survey Act 1974 to oblige the industry to provide JMG with all data, including borehole records, obtained from site investigations.

The increasing interest in this topic led the Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP) to inaugurate a Research Centre for Urban Geology in Nanjing in 2021. BGS is a formal advisor to the centre and has been invited to lead development of its five-year strategic plan. CCOP has also created an Urban Geology Expert Group, and BGS has been commissioned to lead a review of Urban Geology interests in the region.

Box 1 Geoscience for Sustainable Cities impact case study, from the BGS Evaluation report 2021

BGS's urban 3D models continue to be used to address urban challenges, particularly through property attribution and integration within methods for subsurface flow and environmental modelling. Recent applications of existing 3D models include basement heat flow modelling, shallow geothermal modelling (Bidarmaghz *et al.*, 2019), and development of a 3D shrink-swell product (Jones and Hulbert, 2017).

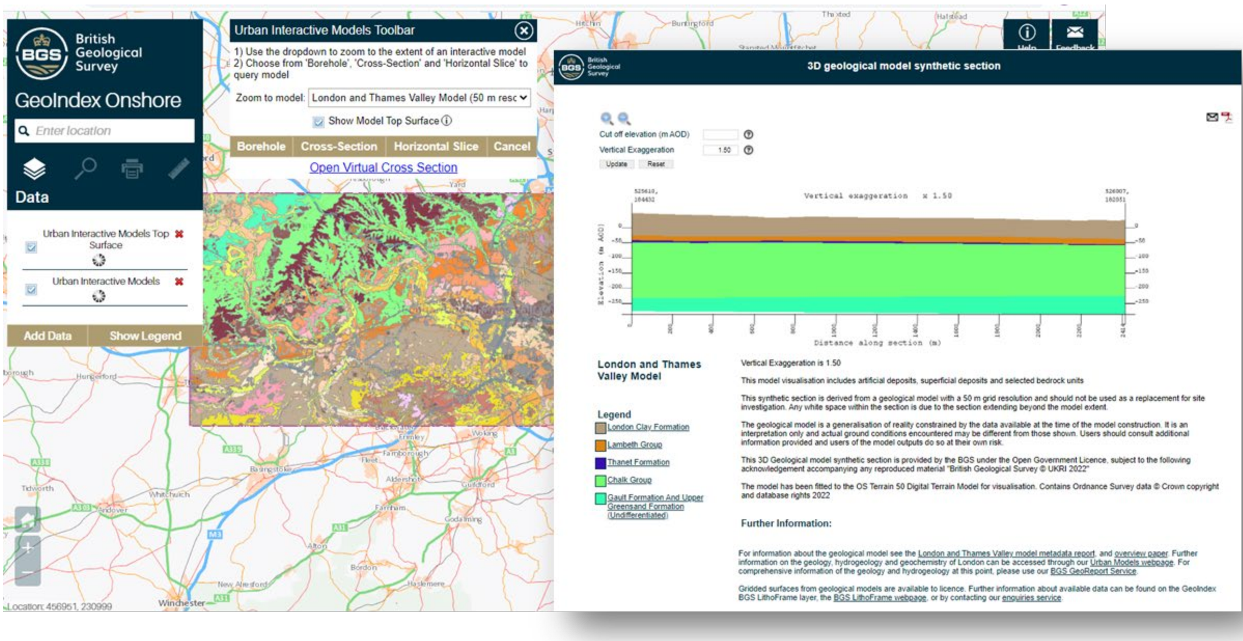


Figure 2 Cross section generated using Urban Interactive model viewer. Note the cross section includes hyperlinks Geological, Hydrological, and Engineering geology reports relevant to that city. (Contains Ordnance Survey data ©Crown Copyright and database rights 2022. Ordnance Survey Licence No. 100021290 EUL.)

Furthermore, the recent delivery of three key urban geological models, Glasgow, London and Cardiff through the Urban Interactive Model viewer has rejuvenated interest in our urban 3D models (Figure 2). The viewer is particularly targeted at providing a service for the geotechnical consultancy sector and is being used to inform the development of conceptual ground models for planning and project design in relation to infrastructure development, groundwater management, and the development of shallow geothermal assets. The web-based delivery tool links Geological, Hydrological, and Engineering geology reports to visualisations of synthetic cross-sections, boreholes and slices derived from the 3D model, providing an entry point to a wide range of BGS literature and data.

The following report reviews the geological, data, and technological contexts for the development of new urban geological models in Great Britain, in order to identify potential impact opportunities and guide future investment. Focusing on 42 towns and cities, this report covers the nature and quantity of urban subsurface data currently available, the geological modelling options, and highlights areas for innovation. It draws attention to the increasing disparity between the observations BGS hold (e.g. borehole) and the baseline datasets which underpin our corporate products. The towns and cities considered in this study include areas already modelled, e.g. Glasgow, Cardiff, London; expected growth areas, such as Leeds and Oxford; regionally important urban centres, such as Birmingham; and 13 Cohort 1 towns identified in the UK Government's Towns Fund, such as Blackpool (Figure 3). The Towns Fund is a £3.6 billion fund investing in towns as part of the government's plan to level up our regions.

Figure 3 Location map of towns and cities (black) and Cohort 1 towns (red) studied in this report (Contains Ordnance Survey data ©Crown Copyright and database rights 2022. Ordnance Survey Licence No. 100021290 EUL.)

2 Quantity and quality of geological observations in the urban sub-surface

BGS geological maps are predominantly constructed using outcrops and geomorphology (feature mapping). Both are scarce in urban settings; instead, boreholes provide one of the main sources of information on the subsurface in these areas. Boreholes are used to inform geological maps in cities, but typically only 10-50 boreholes would be used on a 1:50 000 scale bedrock map sheet. This is a fraction of the subsurface information now available under most cities (Figure 4). These tend to provide a subtly different view of the subsurface from those gained from outcrops and geomorphology, which often do not capture the degree of heterogeneity and discontinuity seen in the subsurface. The sheer number of boreholes provides both a significant resource to improve our understanding of the subsurface for users, and a challenge because of the limits of manual interpretation of borehole records.

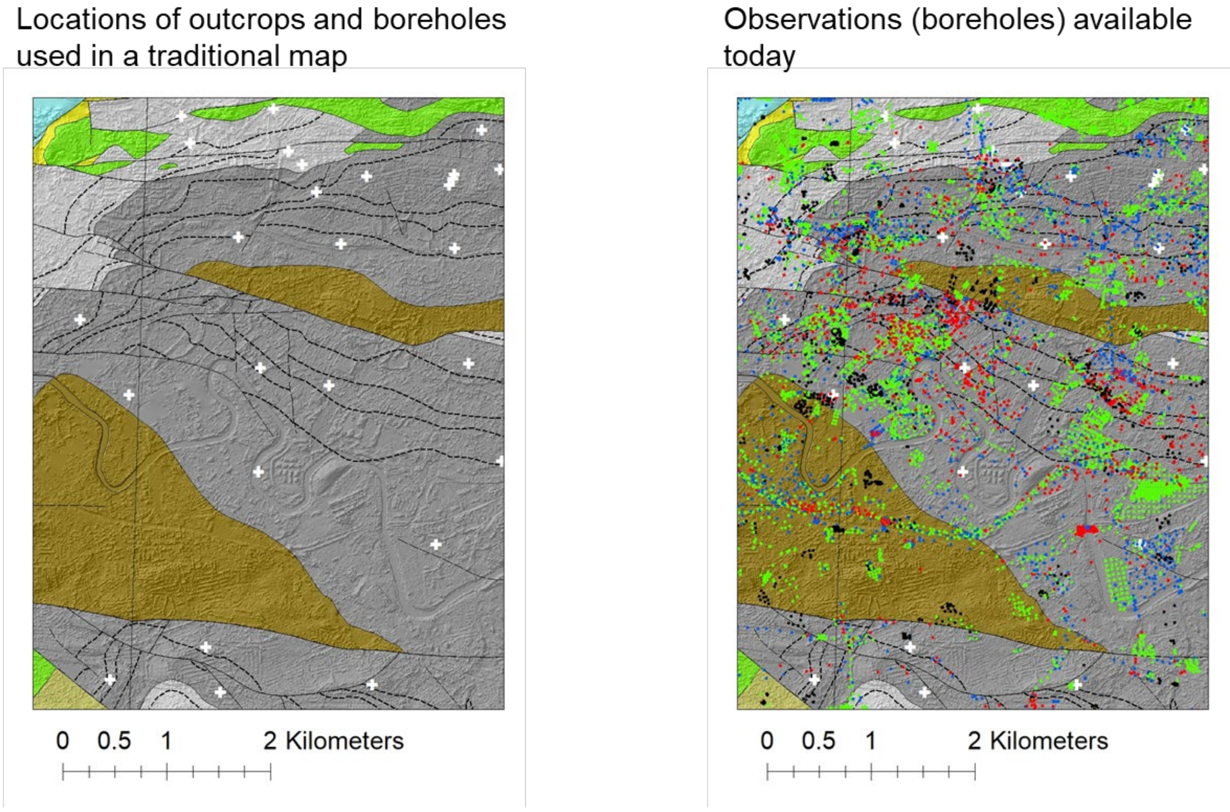


Figure 4 Distribution of available data used to create the geological map (left) and including the current distribution of borehole records (right) in central Glasgow.

Boreholes in the GB range from one metre to fifteen kilometres long and have been drilled for a range of purposes. Most of the boreholes that terminate between 1 and 50 metre depths have been drilled for ground investigation. Those that reach depths between 50 and several hundred metres below the ground surface were typically drilled for groundwater, minerals (including coal), and scientific research. Boreholes deeper than a kilometre were mostly drilled for hydrocarbon prospecting and development.

Borehole records are produced from a geologist's or surveyor's observations of the rock core or chippings extracted from the ground, or interpretation of geophysical logs. Key observations typically include locality and lithological descriptions with depths and thicknesses. The information and level of detail recorded in logs typically varies depending on whether the observer was a driller, geologist or geotechnical specialist. The choice of observer, and the standards or classification schemes used may depend on the purpose for which the borehole was drilled. The use of different lithological classification schemes presents a common challenge in the evaluation and interpretation of borehole records.

BGS holds over 1.4 million borehole records in the Single Onshore Borehole Index (SOBI) which covers boreholes known onshore in the GB.

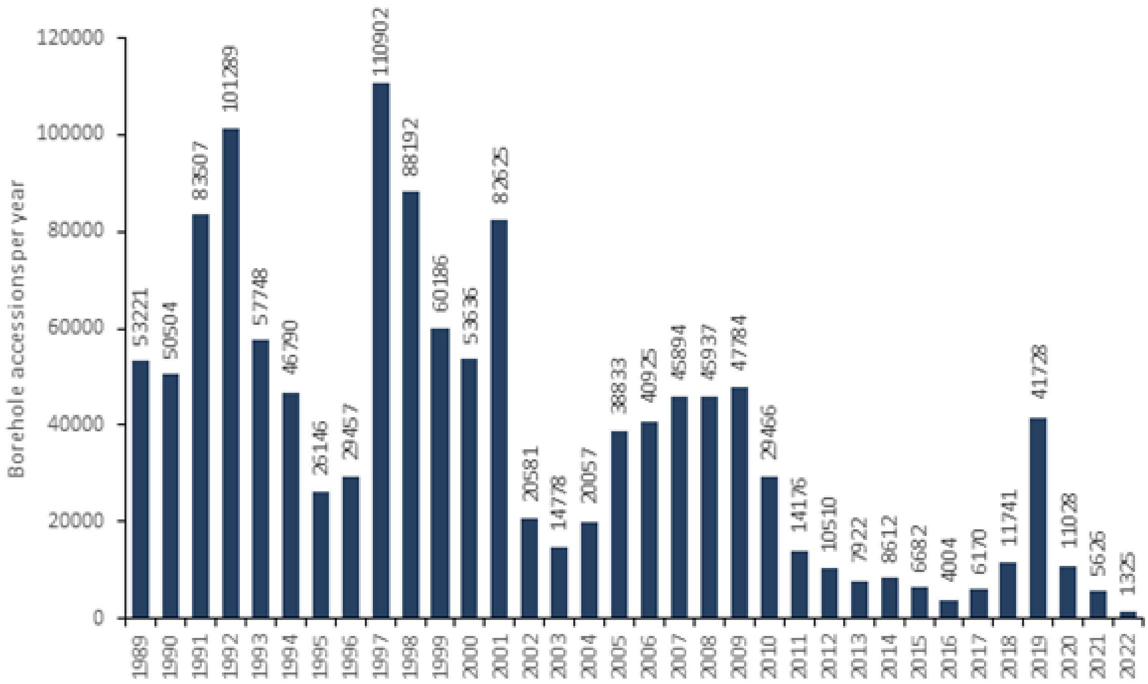


Figure 5 Number of newly acquired boreholes by year in the Single Onshore Boreholes Index. The high peak in 2019 reflects the setup of a system of automatic ingestion of AGS Data**.**

Figure 5 shows the annual number of boreholes added to SOBI from 1989 to 2020. The annual total fell from 8,612 in 2014 to 4,004 in 2016, which coincides with a change in policy, with paper/pdf borehole records no longer routinely added from 2014 onwards. Since then, an index of pdf/paper borehole records has been held in the Digital Accessions Database until project funds are made available for records staff to add them to SOBI.

The high peak in 2019 reflects the setup of a system of automatic ingestion of AGS Data**.** 2018-19 saw a rise in the number of boreholes added to SOBI. One reason for this increase is the Dig to Share initiative, launched in 2018, which builds on the Accessing Subsurface Knowledge (ASK) network (Figure 5, Watson et al. 2007). Dig to Share was set up as a collaboration between BGS and several geotechnical consultancies to encourage the sharing of digital ground investigation borehole records. A repository has been set up to enable consultancies to upload boreholes digitally in AGS format, with the data automatically added to SOBI (the repository can be found at: http://transfer.bgs.ac.uk/ingestion). Data sharing agreements established between BGS and organisations such as the Environment Agency (EA) and Transport Scotland have also increased the number of borehole acquisitions. 197,969 boreholes are located within the 42 urban authority boundaries identified in Figure 3.

While SOBI records the location of a borehole and link to the scan of the log the lithological and stratigraphic logs still need to be digitised. For urban areas located in England only 29% of these boreholes have been stratigraphically coded, in Wales 44% have been coded, while in Scotland it is 66% .Figure 6 and Figure 7 show the proportion of boreholes that have stratigraphic coding in the Borehole Geology database. This can range from over 75% of boreholes in Glasgow to less than 5% in Leicester. Based on the experience of modelling London, Glasgow and Cardiff, the generation of an urban-scale 3D geology model typically requires the inclusion of ~40% of coded boreholes, and a density of at least 10 coded boreholes per km^2.

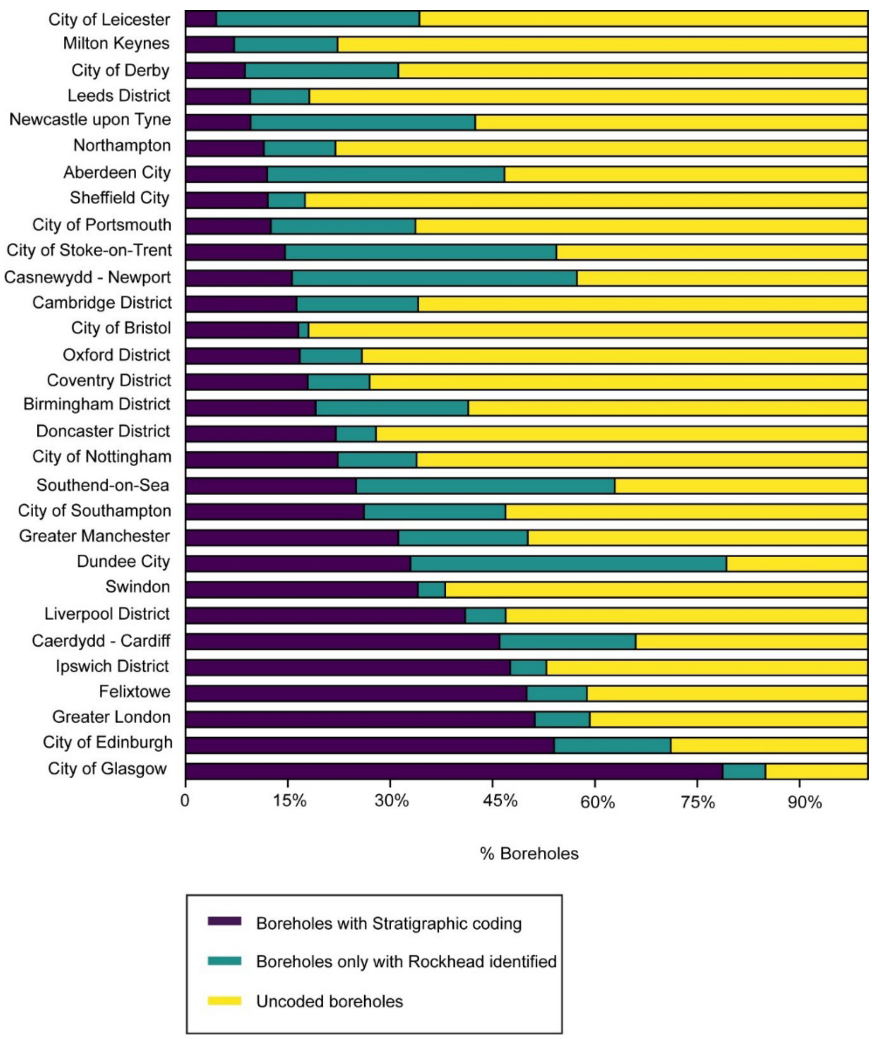


Figure 6 Percentage of coded borehole compared to and partially coded boreholes for the 30 most populous cities in Great Britain

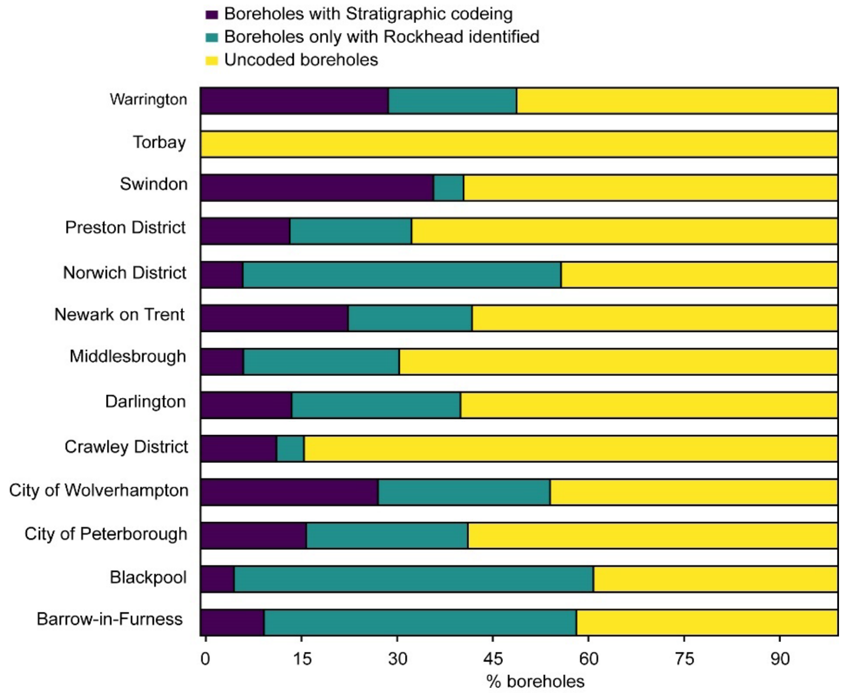


Figure 7 Percentage of coded and partially coded boreholes for the Cohort 1 towns identified by the UK Towns Fund

The increasing volume of borehole data available for geological interpretation and modelling presents the opportunity to create and enhance our geological models, but also is a management challenge. Efficient data capture, evaluation against existing understanding, and integration in 2D and 3D baseline datasets are needed to streamline processes and minimise costs. Innovation in the use of novel data analytic methods and data management technologies is needed to ensure BGS can extract value, and achieve impact, from the effective use of our borehole data assets.

2.1 ISSUES IN USING GROUND INVESTIGATION BOREHOLES TO CONSTRUCT STRATIGRAPHY

Stratigraphy provides the most reliable way to correlate lithology and other geological properties in the subsurface, as it uses geological process understanding to correlate between disparate observations. However, the conventional lithostratigraphy developed for BGS geological maps, which was created for interpretation of field observations, can be hard to apply to sub-surface borehole data. Diagnostic features and properties that are evident from outcrop and feature mapping may not be observable in the majority of ground investigation boreholes drilled in urban areas. Some of the key issues with stratigraphic interpretation of ground investigation data for geological modelling are:

- Identifying features such as fossil horizons, changes in clast composition, and sedimentary structures, are rarely recorded in ground investigation boreholes.
- The BS5930 classification scheme for lithology used by most geotechnical contractors differs from the classification schemes used by geologists. For instance, Dolomite ($CaMg(CO_3)_2$), which is a key diagnostic lithology of many units in the Carboniferous, Permo-Triassic and Jurassic, is described as 'limestone' in most ground investigation boreholes because it reacts with HCL. However, geologists only use the term 'limestone' to refer to calcium carbonates ($CaCO_3$).
- Revisions to stratigraphic nomenclature since the borehole was drilled and interpreted.
- Limited lithological detail recorded in the borehole log, particularly where only drillers logs are available.
- The level of discoverable understanding about the key diagnostic features of particular stratigraphic units in the BGS databases, such as diagnostic fauna.

Some of these issues can be resolved during geological interpretation, through the application of conceptual understanding and the use of other properties that are recorded in ground investigation data. For instance, using stiffness to differentiate subglacial till from post-glacial sediments with similar lithological descriptions (Kearsey *et al.*, 2015). However, in some cases it may be impossible to confidently identify stratigraphic boundaries for ground investigation boreholes. In such cases, it may be necessary to modify the stratigraphic framework used on geological maps to better reflect the nature of the interpretation in the 3D geological model.

3 The geological contexts for towns and cities

The towns and cities of Great Britain are built on a diverse range of geologies which determine everything from their groundwater flow and building conditions to geothermal potential. Superficial deposits are on average 8 metres thick but can be as thick as 108 metres under some cites. Bedrock lithologies range from poorly consolidated sandstones to granite and from flat lying to faulted and folded.

3.1 THE BEDROCK CONTEXT

The ages of bedrock units that underlie the selected towns and cities are shown in Figure 8. Carboniferous, Jurassic, Triassic and Palaeogene rocks collectively underlie 84% of these towns and cities by geographical area. The high proportion of Carboniferous rocks beneath the towns and cities is due to the proximity to coal, iron and limestone resources, which controlled the growth of industrial centres in the 19th and 20th centuries. Appendix 1 presents summary statistics on the geological settings of the selected towns and cities.

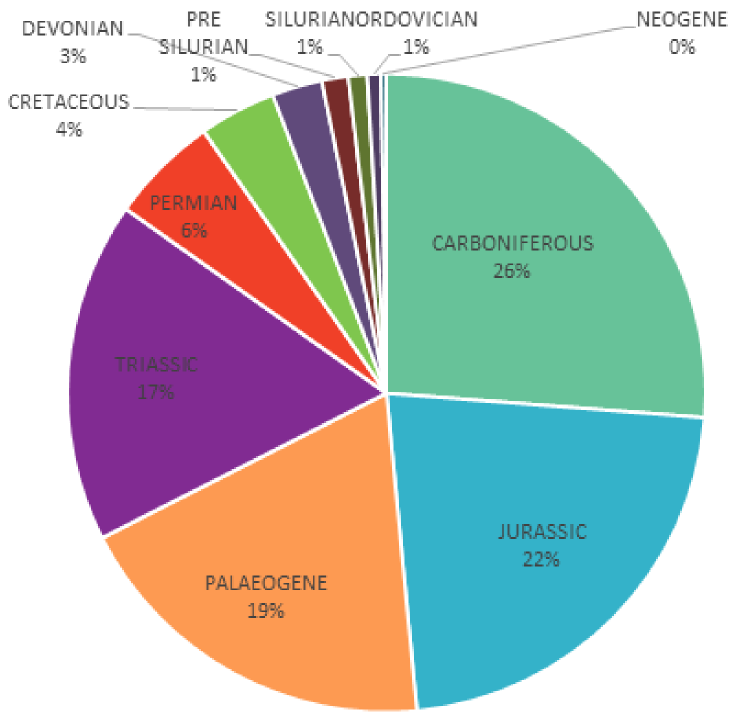


Figure 8 Ages of bedrock units underlying towns & cities by area of coverage

A summary of the number of bedrock units and availability of digital structural data (e.g. dip and strike measurements), for the selected town and cities is provided in Appendix 1. Figure 9 shows the number of mapped bedrock units within the urban limit ranges from 3 (Norwich and Crawley) to 67 (Greater Manchester). Geological structural complexity (faulting, folding etc.) and the number of bedrock units can vary between map sheets depending in the age of the mapping. For example, Newark on Trent lies at the corners of four 1:50,000 scale map sheets (Ollerton, Lincoln, Nottingham, and Grantham).

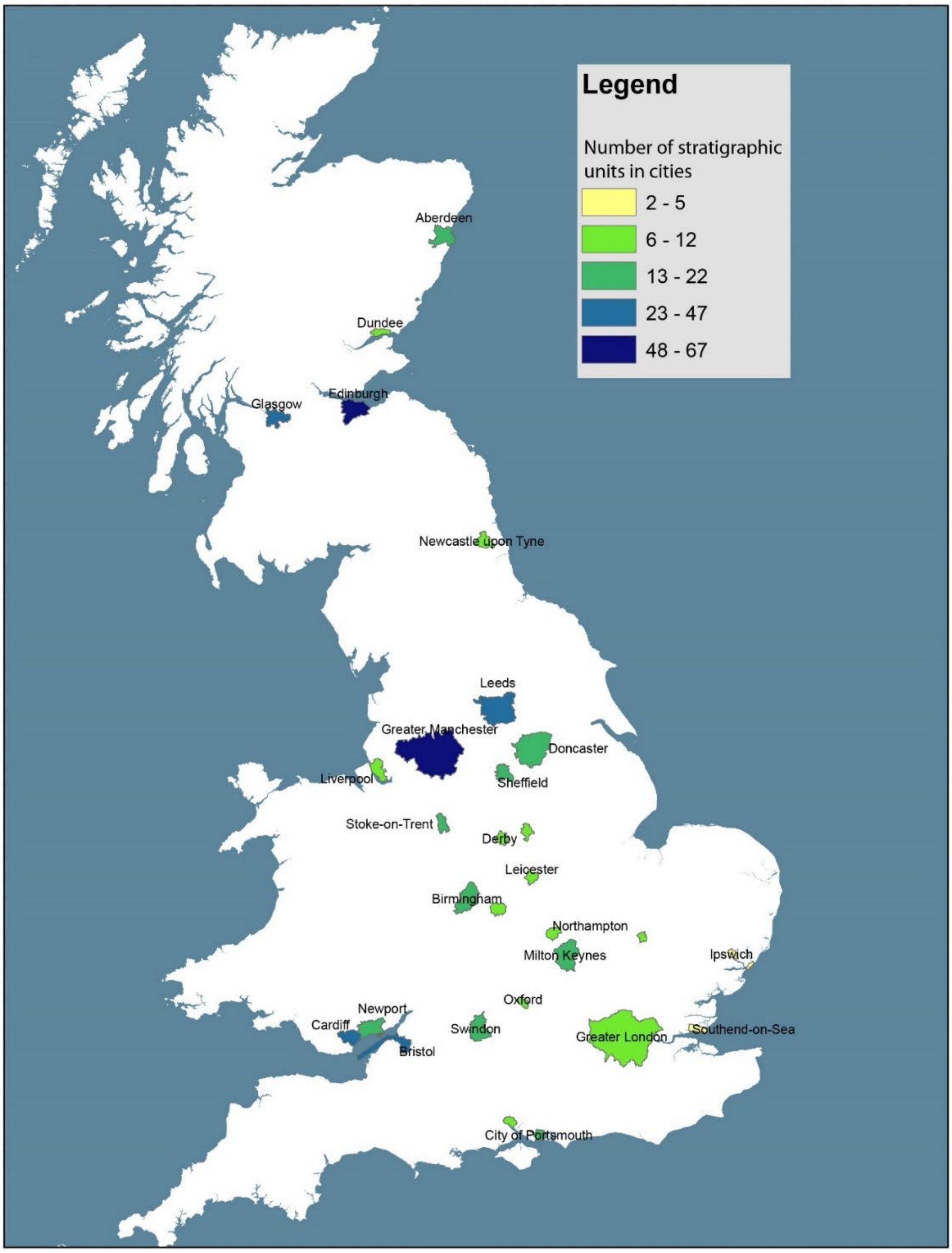


Figure 9 Heat map of number of bedrock units under cities in GB. The cites that sit above major unconformities have the most geological units. (Contains Ordnance Survey data ©Crown Copyright and database rights 2022. Ordnance Survey Licence No. 100021290 EUL.)

The number of faults in cities also variable (Figure 10) with the total length of faults mapped in cities ranging from 0km to as much as 1968km in cites like Manchester or Leeds. Faulting is most common in cites which overly Coal Measures strata, possibly indicating the importance of mine plans in the identification of faults under cites. These cities will be more challenging to create 3D geological models in because the kinematics of the faults will need to be understood.

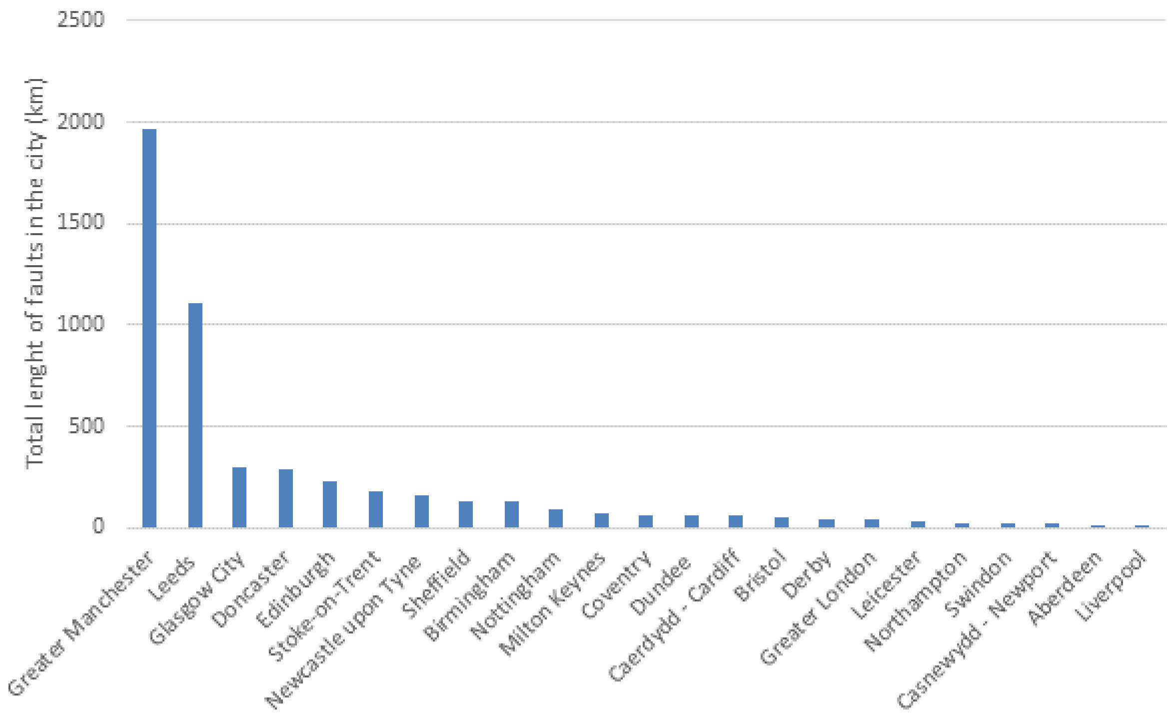


Figure 10 Total length of faults under GB Cities.

3.2 THE SUPERFICAL CONTEXT

The superficial deposits under the studied cities are variable and complex. They represent between 0.1% and 5% of the volume of the top 100 metres under study cities (Figure 11). However, these deposits often account for the most complicated ground conditions (Terrington *et al.* 2021). The average thickness of superficial deposits under the studied cites is 8.07m, yet the maximum is 108m (Figure 12). Four towns and cities have maximum thicknesses of superficial deposits that locally exceed 100m: Glasgow, Greater Manchester, Liverpool and Barrow-in-Furness. Widespread glacial deposits are present in these areas and the exceptional superficial deposit thicknesses are likely to be associated with buried valleys, deep sediment filled channel-like features with no surface expression that are only revealed through boreholes/geological models. The high variation in the thickness of superficial deposits means that their characterization under cities is critical.

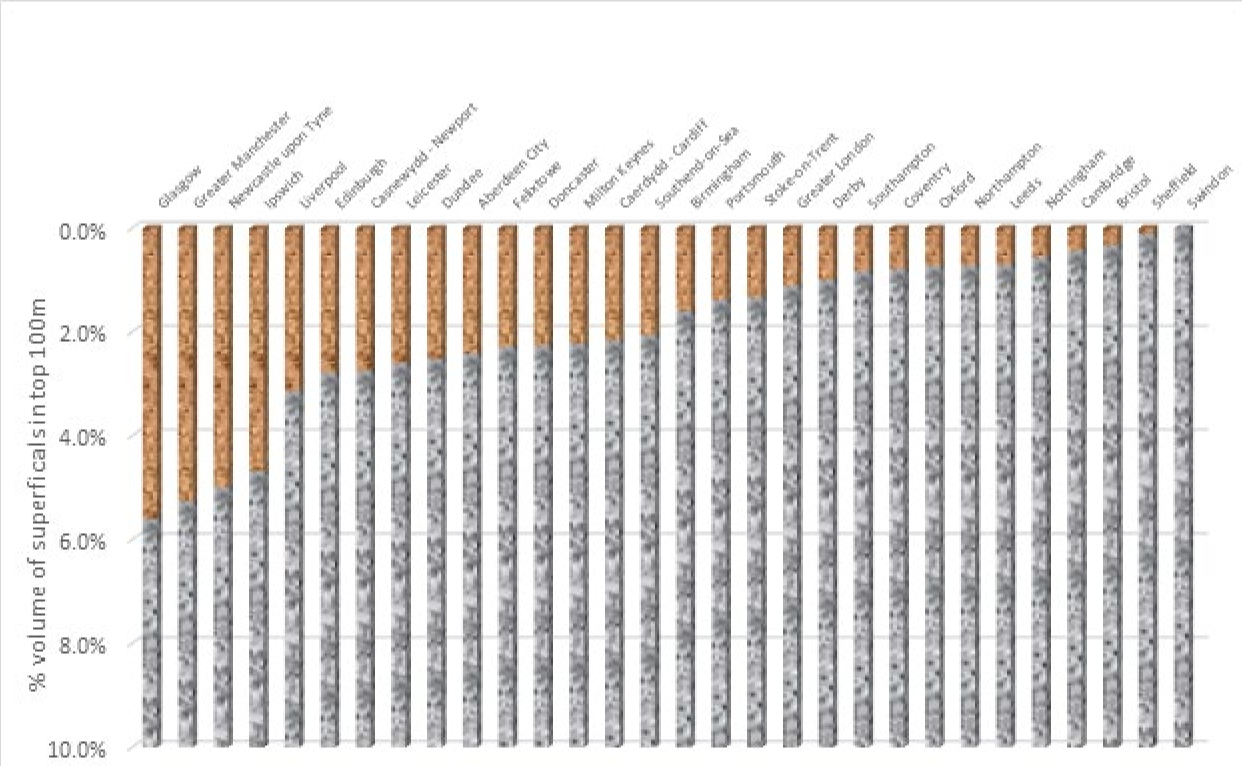


Figure 11 Percent volume of the top 100m under the study cities made up of superficial deposits

Figure 12 Maximum thickness superficial deposits discovered under the study cities

The number of mapped Quaternary units for each town/city is shown in Appendix 2. The values range from 5 (Bristol, Crawley, Wolverhampton) to 30 (Greater London). As with the bedrock, the number of mapped Quaternary units in an area does not necessarily reflect the geological complexity. London has 30 Quaternary units because the Thames terraces are individually named, but the succession is relatively simple because typically only 2-3 Quaternary units are stacked in a given location. The greatest complexity in the Quaternary tends to be glaciated areas, where the geological maps do not indicate the number or extent of buried units where widespread till is mapped, but boreholes can reveal the complex geometries of the units. It can be difficult to interpret the geological units in these scenarios, particularly where multiple ice advance/retreat cycles have occurred.

The city of Manchester provides an example where high geological complexity in the superficial deposits is revealed by the borehole data. Till is widely mapped in the area, which gives the impression of a homogenous blanket. However, boreholes used to construct the central Manchester 3D geological model reveal thick lenses of glacial sand & gravel (pink) and laminated clay (purple) encased within the till. The main purpose of the Manchester model was to assess the permeability of the superficial deposits. These sand & gravel bodies affect the permeability of the till and can be aquifers in their own right.

The dominant Quaternary sediment type in the selected cities is river terrace deposits, which underlie 26% of the total area (Figure 13). Perhaps surprisingly given its relatively ubiquitous nature, alluvium only covers only 4% of the total area, but its ribbon-like form accounts for this. Areas where superficial deposits are known to exist but are not defined are mapped as 'superficial deposits' and are classed as unknown. For example, extensive 'superficial deposits' are mapped either side of the River Clyde in Glasgow, which correspond with former wharves and shipbuilding yards. In these areas made ground obscures the underlying superficial deposits.

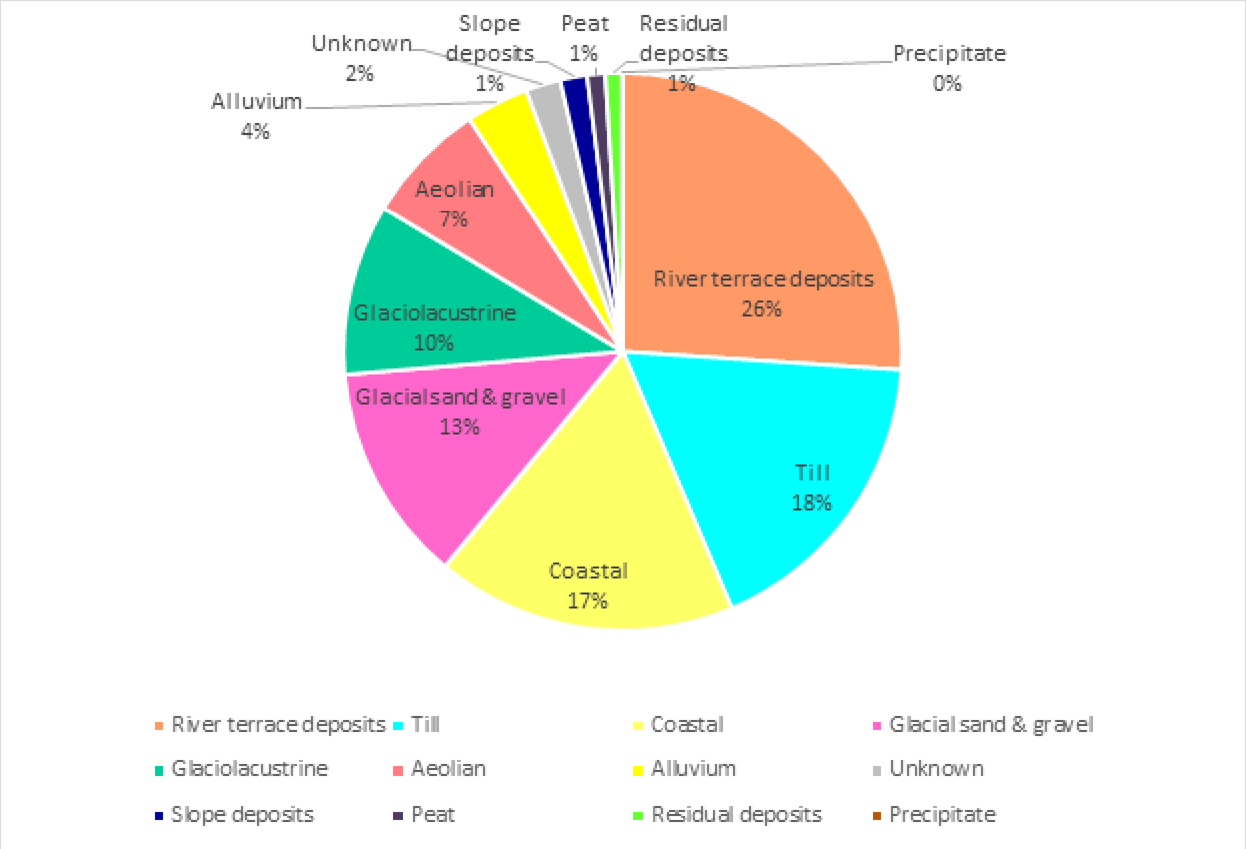


Figure 13 Plot of Quaternary sediment type by area for the towns and cities in the study. Similar deposits were grouped regardless of age, such as river terrace deposits, tills, glacial sands and gravels. Coastal deposits include tidal flat and salt marsh sediments. Aeolian sediments include loessic deposits such as Langley Silt Member in the Thames Valley and wind-blown sands. Slope deposits include head and colluvium; alluvium includes alluvial fan deposits and Holocene lake deposits; residual deposits include clay with flints; and tufa is classed as precipitate

4 Age of mapping

An assessment of survey dates was carried out for the 1:50 000 scale geological maps that cover England, Scotland and Wales (Figure 14) shows that some sheets have not been surveyed since the 1880s. Table 2 lists the towns and cities covered in this report with the publication and survey dates of the corresponding 1:50 000 scale geology maps. All maps are listed for those towns and cities that cover multiple sheets.

The date when many of the cites in the GB were last mapped ranges from 1882 to 2016 and the median date of last survey is 1992. The publication dates on 1:50 000 scale geological maps do not always correspond with the time of survey. Minor bedrock revisions may have been carried out following a desk based seismic and/or borehole or mine plan interpretation, and the map re-published, but the superficial deposits may not have been surveyed for 100 years. The Saffron Walden sheet, for example, has a publication date of 2002, giving the impression that the area last surveyed at that time. However, the original survey of the area was carried out in 1881-82 and partial re-surveys were carried out in 1930-31, 1936, 1952, 1978-83 and 1987. The entire map was revised in 2000 but not re-surveyed, therefore the map sheet still contains original 1881-82 interpretations. This means the geological linework shown may have been drawn before the discovery of plate tectonics or the knowledge that the GB was covered by multiple different glaciations rather than one. Furthermore, advances in geological chronology, mapping methods and availability of airborne imagery and digital terrain models means that edge match issues are always going to be present between maps with such widely varying vintages.

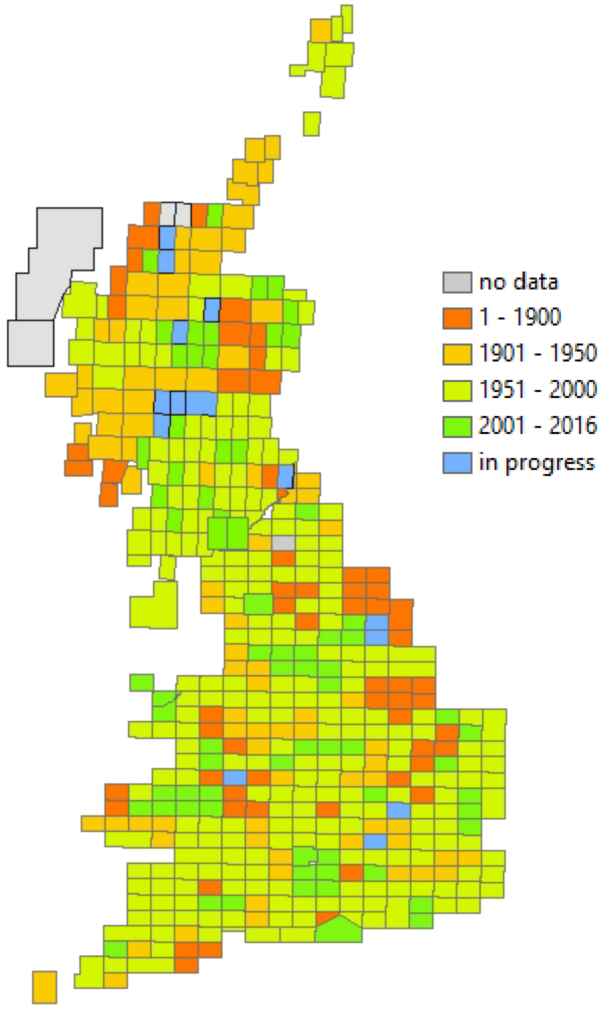


Figure 14 Assessment of survey dates for all 1:50 000 geological map sheets in England, Scotland and Wales

Continuity differences can clearly be seen in the bedrock units at the boundaries between these maps (Figure 15). On the Ollerton sheet the Mercia Mudstone Group is not subdivided, whereas on the Nottingham sheet to the south the Mercia Mudstone is divided into four subunits (Gunthorpe Member, Edwalton Member, Branscombe Mudstone Formation and Blue Anchor Formation). Similarly, Penarth Group is mapped on the Ollerton/Lincoln sheets but is split into Westbury Formation and Cotham Member on the Nottingham sheet. Lastly, the Scunthorpe Mudstone Formation is subdivided into the Barnstone Member, Barnby Member and Granby Member on the Grantham sheet, but not on the Lincoln sheet to the north. These sheet boundary mismatches would need to be resolved and possibly a new stratigraphy created, if a 3D geological was created for the area.

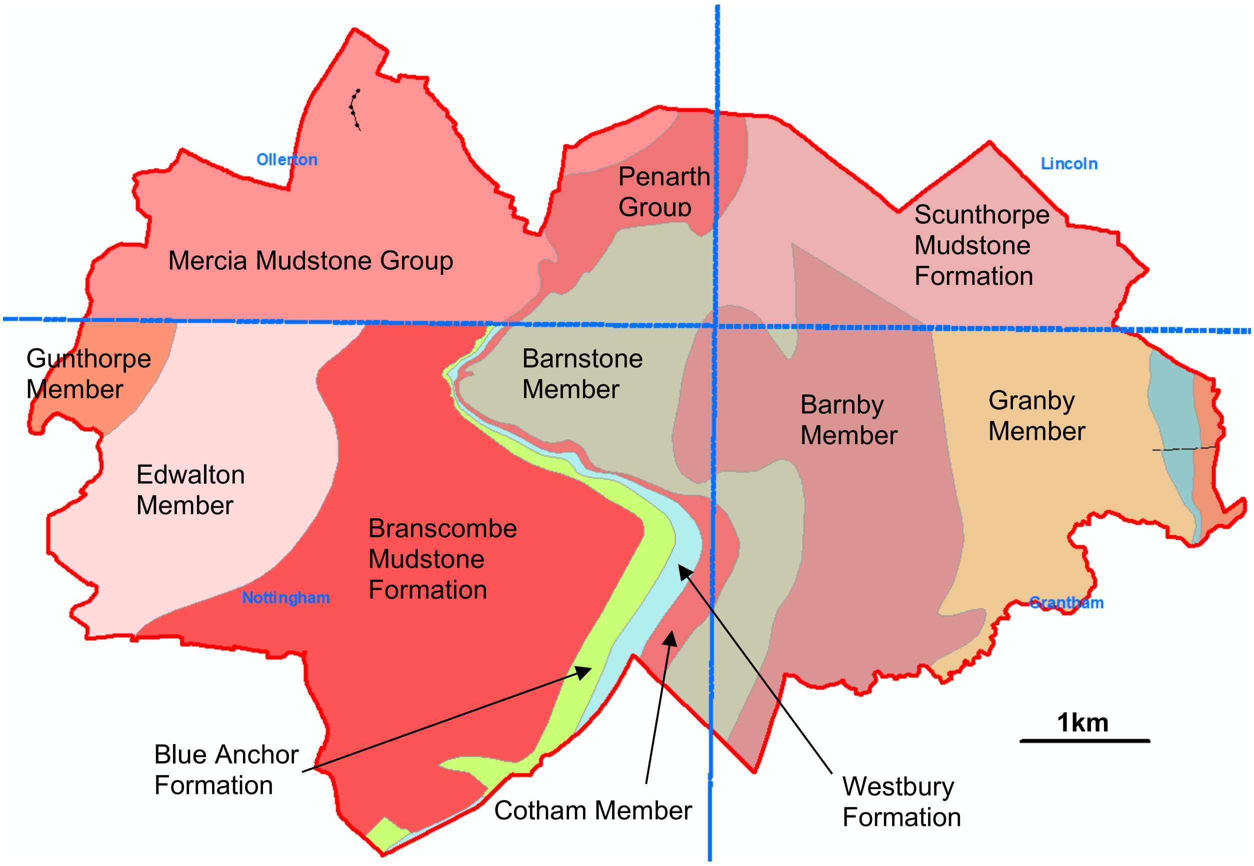


Figure 15 Bedrock geology map of Newark on Trent showing bedrock continuity differences at 1:50,000 scale map sheet boundaries

5 Current methods BGS urban 3D geological modelling

Since completion of the London and Glasgow cross-cutting projects urban geological modelling for British urban areas has been limited. However, our overseas urban modelling projects such as Singapore and Kuala Lumpur have allowed us to innovate in representing more complicated bedrock geology. This experience and advances software may present the opportunity to revisit our workflows and enhance efficiency in the modelling process.

5.1 PRACTICAL LIMIATIONS IN MODELLING WORKFLOWS

A survey of seventeen BGS geological modellers found that an average model takes 20-30 days to build. Most of the time is taken up in the geological interpretation (Figure 16). This includes coding boreholes, correlating cross-sections, and interpreting geophysics. This also includes checks and refinements needed to improve the model calculation.

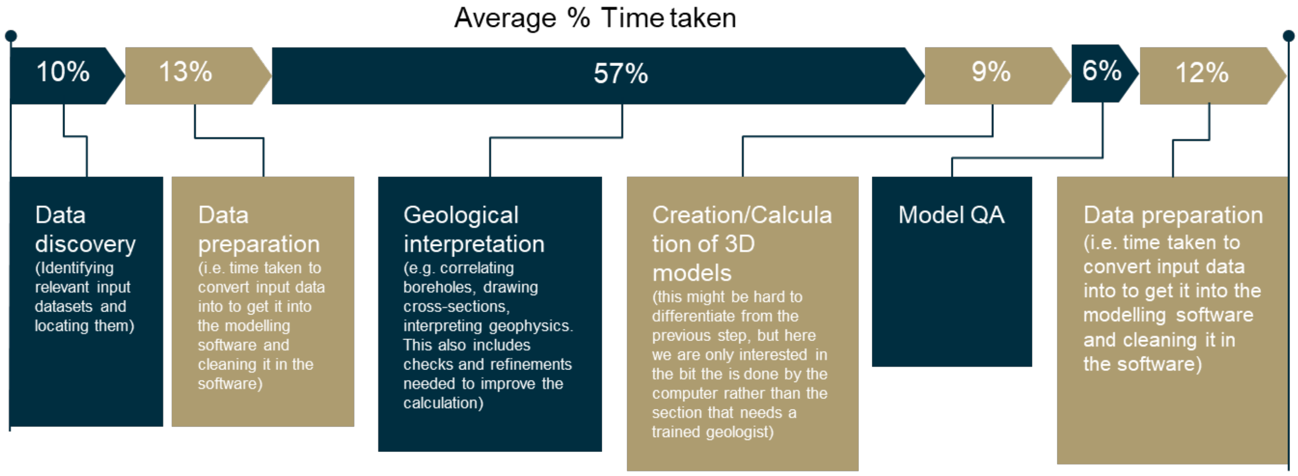


Figure 16 The standard modelling workflow used to create geological models in BGS. With the average time spent on each section marked. Note the majority of the time is spent doing the Geological interpretation.

5.2 SUMMARY OF CURRENT BGS SOFTWARE AND CAPABILITY

BGS currently has a range of software available for 3D geology modelling, from state-of-the-art hydrocarbons systems tools such as SKUA-GOCAD and Petrel, to in-house developed programs such as Groundhog. Table 1).

Groundhog cannot model faulted bedrock geology so technically can only be used for combined bedrock and superficial modelling under four of the 42 cities identified.

SKUA-GOCAD and Petrel could be used to model faulted bedrock as well as superficial geology under GB cities but neither are designed for use with urban datasets, and a large amount of manipulation of map and borehole data are required to use them in urban applications. It has also been used to do Lithological property modelling (e.g. stochastic modelling) to create more accurate predictions of lithology than can be achieved with lithostratigraphy (Kearsey *et al.* 2015).

Open Source software and code from the LOOP consortium provides tools for creating bedrock models directly from geological maps in a very short time. It uses the same algorithms (implicit modelling) as SKUA-GOCAD but adapted to geological maps. It also has the advantage of not being restricted to a specific number of licences. However, it has some limitations which means it cannot be used to completely model urban geology at the moment:

- The code has to be modified to include borehole information
- It only models bedrock geology
- It is code based so may be challenging for some geologist to run

Strategic development of urban models will require assessment of additional software tools and capability. Options include a range of modelling applications used by other geological surveys and underground experts for shallow geological contexts (<200m depth) such as:

- Geoscene3D (https://geoscene3d.com/) is used by the United States Geological Survey (USGS), the Swedish Geological Survey, the Geological Survey of Denmark (GEUS), Illinois State Geological Survey and the Polish Geological institute to build near surface geological models.
- Leapfrog Geo (https://www.seequent.com/products-solutions/leapfrog-geo/) is now widely used in the mining and engineering geology sectors as well as by the Australian and some European geological surveys.

Table 1 Comparison of LOOP Structural to other 3D Geological modelling software currently being used in BGS

Software	Input data	Type of geology modelled	Calculation method	Time for geologist create models
GSI3D*	Maps Boreholes 2D geophysics	Unfaulted near surface deposits	Direct triangulation	Weeks - months
Groundhog	Maps Boreholes 2D geophysics	Unfaulted near surface deposits	Interpolation (currently nearest neighbour)	Days - weeks
LOOP Structural	Maps Boreholes (although not tested) 2D and 3D geophysics Structural dip information	Faulted and folded near surface deposits (unfaulted may be possible but not tested)	Implicit	Hours
GOCAD *(this is now part of SKUA-GOCAD but refers to the standard, non-implicit, workflow modules)*	Maps Boreholes 2D and 3D geophysics Structural dip information (although labour intensive)	Unfaulted, Faulted and folded near surface deposits Seismic depth converted surfaces and mine workings	Interpolation (Discrete Smoothing Interpolation)	Weeks - months
Petrel	Maps Boreholes 2D and 3D geophysics Structural dip information	Faulted and folded deposits Seismic interpretation and depth conversion	Implicit	Days - weeks
SKUA GOCAD	Maps Boreholes 2D and 3D geophysics Structural dip information	Unfaulted, Faulted and folded near surface deposits. Seismic depth converted surfaces and mine workings	Implicit	Days - weeks

* BGS in-house development. Last version was released in 2013 – the software is no longer supported. The software has been superseded by Groundhog.

5.3 UPDATING MODELS

Models can be split into the **interpreted elements**, such as stratigraphic borehole interpretations, fault traces, cross sections, outcrop and subcrop maps and **calculated elements** e.g. surfaces, grids, shells, volumes. If you put the same **interpreted elements** in a different calculation engine (e.g. direct triangulation, interpolation or implicit) you will get different results (calculated elements). Therefore, models created using different software will differ, which makes it almost impossible to re-use calculated elements as it is near impossible to recreate identical calculated elements in different software.

Interpreted elements can be re-used in different software but, depending on the calculation engine, fewer interpreted elements may be needed to create a similar result. For instance, a GSI3D model (which uses direct triangulation) might have 50 cross sections, while an implicit model of the same geology may only need 5 to create surfaces in similar geology. Test studies are needed to understand if, and how, changing software and calculation engine affect the predictive accuracy of a model.

5.4 MODEL DELIVERY

There are a wide range of model delivery methods currently in use at BGS (Figure 17). The process of model review and QA is a key requirement for model delivery to external users. How, and what in a model needs to be checked depends on the delivery pathway for that data. For instance, a model approved for a 3D PDF may not be appropriate to deliver in native format (i.e. software-specific file) to an end user. The degree that the end user can interact with, compare their data with, or re-use the model or its constituent elements, affects how a model is QA checked.

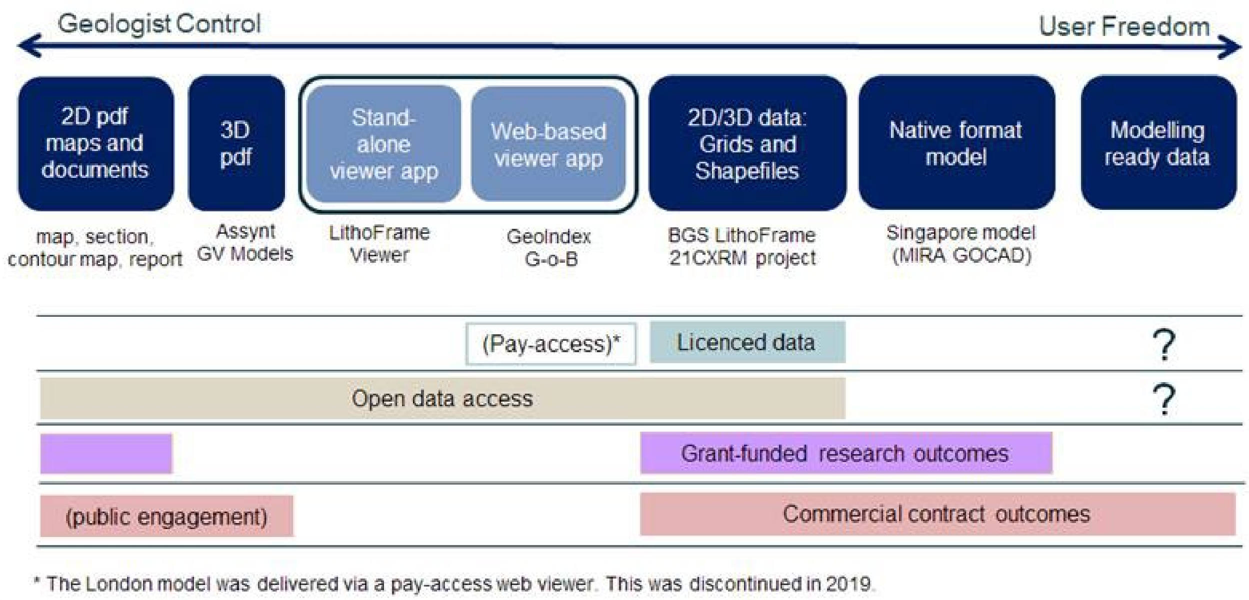


Figure 17 Different methods of model delivery currently in use by BGS (courtesy of Katie Whitbread)

BGS currently delivers Urban models using a range of methods. The 3D geology models for London, Glasgow and Cardiff are available to view, without charge, Urban Interactive Models Tool within on our Onshore GeoIndex viewer through the 3D surfaces and grids from these models and others that have been through the National Geological Model signoff procedure under the BGS LithoFrame delivery route. Some models have been turned into 3D PDFs but this is mostly done for specific clients or stakeholders and focuses on the particular requirements of users.

6 Future of urban geological modelling

Urban contexts provide specific drivers that influence the design and content of the geological model. Urban models need to:

1. Make predictions relevant to urban scales of interest e.g. development and infrastructure sites
2. Be efficient to develop and easily updateable, to suit the more local-scale, higher turnover of urban projects
3. Capture the lithological variability within geological units as relevant to engineering geological and hydrogeological considerations using methods like lithogical property modelling (c.f. Kearsey *et al.* 2015)
4. Enable model outputs to be delivered in a range of formats and be interoperable with other urban and built environment data management and decision-making tools- e.g. Building Information Management (BIM) compatible
5. Have an automatic/semi-automatic calculation of the accuracy/uncertainty of the model in the workflow for integration within risk management workflows in ground models.

3D geological modelling is increasingly becoming common practise in in geotechnical and groundwater consultancy. The development of embedded 3D modelling capability within industry raises the prospect that BGS's role may need to shift from *informing* users through the provision of models and associated knowledge, to *enabling* users to create relevant knowledge themselves. The latter will require the delivery of QA'd baseline data, as well as services to review models and interpretations created by consultants. This shift will require a renewed emphasis on BGS geological expertise, and a new approach to the provision of data services.

Previous BGS modelling workflows in urban areas have been focused on trying to replicate the geology map in 3D, which can cause issues if the borehole data contradicts what is shown on the geological maps, and the methods used to create the geological interpretation (e.g. GSI3D). In future, greater emphasis on understanding and communicating why these differences occur will be needed to inform stakeholders.

6.1 USER DEMAND FOR 3D URBAN MODELS

The delivery of Glasgow, London and Cardiff through the Urban Interactive Model viewer (Figure 2) has shown there is user demand for 3D urban models. In the first six months after the release of the viewer the Urban 3D models had an average of 40 hits per month, excluding the first month which had an elevated hit count due to the launch (Figure 18). This is a comparable number to the BGS Landslides dataset, which is the most extensive source of information on landslides in Great Britain. We would expect that as we add more cities to this viewer that the number of users would grow.

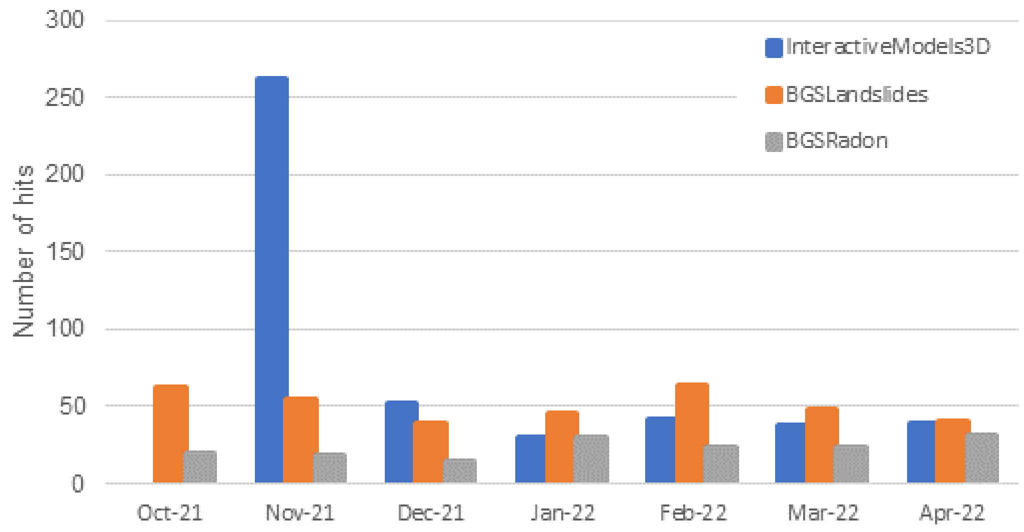


Figure 18 Number of website hits that the Urban Interactive Model viewer has gained in the first 6 months of its launch. The hits on the BGS Landslides and BGS Radon datasets are included for comparison.

Stakeholder feedback from the launch of the Urban Interactive Model viewer also highlights the utility of Urban 3D modelling to GI design. Below are two testimonials from external users.

"The borehole function was very useful to identify quickly the stratigraphy/thickness of units beneath the site/project area … It takes ~2 mins to get the stratigraphy for the site using the tool – without the tool they'd have to check different BHs nearby in their webviewer and cross-correlate, takes much longer and not always enough BHs nearby."

Heidi Bignell – EA

"Fantastic to see the BGS making this tool available for free."

"[The Tool] will be very useful at the desktop study stage or for planning GIs in Cardiff in getting a ballpark estimate of made ground/superficial thicknesses much more quickly than trawling through borehole records. Compared to a recent GI in Cardiff and the Glacial Till thickness was roughly where we'd estimated from borehole records and confirmed during GI. Had a look at the London model as well – this would have been a big timesaver for abstraction borehole prognoses when compared to going through the London Memoir and reading off the depth contour and isopachyte maps."

Peter Murphy – Tetra Tech

Users of the geological models highlight that they deliver information that is not shown on our digital maps such as the stratigraphic order and thickness of units. Furthermore, the use of bespoke 3D geological models results in an estimated 10% efficiency saving in drilling for ground investigation (Bricker *et al.* 2022) so 3D models will be critical in delivering the 'Build Back Better' initiative and 'Levelling Up' agenda. We are also seeing an increasing demand from the shallow geothermal sector for such data.

6.2 OPPORTUNITIES FOR FUTURE 3D URBAN MODELS

An evaluation of the demand and opportunity for future 3D urban geology modelling has been completed for a subset of towns and cities in Great Britain (Appendix 1 and 2). These locations include our largest urban centres. Places identified as hubs for urban innovation by the UK Government lie along strategic transport routes and/or are earmarked for future urban development e.g. Towns Fund.

The following urban centres have an existing BGS 3D geological model at approximately 1:50,000 scale:

- Glasgow (superficial and faulted bedrock)
- Greater London and the Thames Valley, including Reading, High Wycombe, Slough; Maidenhead, Bracknell, and Didcot (superficial and unfaulted bedrock)
- Cardiff (superficial deposits only)
- Manchester - only part of city (superficial deposits only)
- Liverpool (superficial deposits only)
- Ipswich (superficial and unfaulted bedrock)
- York - only part of city (superficial deposits only)

6.2.1 Cities with a greater need for 3D urban modelling

The subset of strategic towns and cities (Figure 3, Appendix 1 and 2) was further evaluated and refined to identify places with greatest opportunity for impact from development of an urban geological model BGS 3D urban modelling based on:

i) Urban development priority: does the town or city lie along a strategic transport corridor (HS2; M4) or development corridor? (Cambridge-Milton Keynes-Oxford-London arc; Northern Powerhouse) Is the town or city home to a strategic port?

ii) Complexity of the shallow geology:
  a. For towns and cities where the surface geology is dominated by superficial cover (>70% cover) the thickness and variability of superficial deposits has been considered using the Superficial Drift Thickness Model (SDTM).
  b. For towns and cities dominated by bedrock at surface the complexity of the bedrock geology (type/faulting/folding) has been considered. Mining legacy has also been accounted for.

A three-stage assessment was then carried out to identify the priority towns and cities for 3D Urban modelling:

1. Those cities which already have existing models, which have been delivered through the Urban Interactive Models Tool, were removed from the list
2. The rest were ranked based on the number of Urban development priorities and number of available coded boreholes (Section 2).
3. Then ranked by complexity of the geology (Section 3) from more complicated to less complicated.

Based on this evaluation process the following locations are considered to be a higher priority for 3D geological characterisation:

Tier 1 (Highest priority) - Greater Manchester (updates); Liverpool (updates) Newcastle (and Gateshead); Leeds; Sheffield; Milton Keynes

Tier 2 (Secondary priority) – Bristol, Nottingham, Stoke-on-Trent, Edinburgh, Birmingham

6.2.2 Capacity for development of 3D urban models for high priority towns and cities

For locations considered to be a higher priority (tier 1 and 2) for 3D geological characterisation an assessment of the capacity to undertake 3D geological modelling based on borehole data availability and age of geological mapping has been undertaken and summarised in Table 2 below. Other than Greater Manchester, Liverpool and Edinburgh there needs to be significant investment in stratigraphic borehole interpretation to generate an urban scale geological model base on the experiences from London and Glasgow. The bias towards shallower urban boreholes derived from ground investigations may impact on the accuracy of the urban model at depth, particularly where the bedrock geology is highly variable.

Table 2 Assessment of capacity for urban modelling in higher priority areas

	% Coded boreholes for lithostratigraphy	Borehole length (75th percentile)	Geological mapping Date of Survey	Map sheet issues
Greater Manchester	31%	11.12	Covers 8 50K sheets. North last surveyed 2003-2012, south 1951/1961, west 1932/1938.	No obvious mismatches at sheet boundaries but less confidence in older mapping.
Liverpool	41%	8.1	Covers 4 50K sheets. Survey dates are 2000 and 1932-1938.	Majority of area covered by older mapping. Mismatches at sheet boundaries.
Sheffield	12%	13	Covers 2 50K sheets, both surveyed in 2005.	-
Newcastle	10%	13	Covers 4 50K sheets. Most of the area was last surveyed in 1983/1996 and a small area in 1932/1975.	Mismatches at sheet boundaries.
Leeds	9%	11.5	Covers 4 50K map sheets. Survey dates are 1995/1996 and 2001/2003.	-
Milton Keynes	7%	-	Covers 4 50K map sheets. Survey dates are 1964, 1990, 2000 and 2004.	Mismatches at sheet boundaries. Inconsistent subdivision of Oxford Clay Formation.
Nottingham	22%	9.99	Covers 3 50K map sheets. Survey dates are 1966, 1993, 1996 and 1999.	Mismatches at sheet boundaries.
Bristol	17%	24.48	Covers 4 50K map sheets. Survey dates 1939, 1953, 1975 and 1980.	Mismatches at sheet boundaries.
Stoke-on-Trent	15%	-	Covered by 1 50K map sheet. Survey date 1992.	-
Edinburgh	54%	12	Covered by 2 50K map sheets. Survey dates 2006/2007.	Minor mismatch in superficial deposits at sheet boundary.

6.3 BOREHOLE STRATIGRAPHIC INTERPERATIONS

The unique feature of urban geological modelling is the quantity of borehole data available, which represents a step-change in our observations of the subsurface. However, currently borehole interpretation has to be undertaken manually, borehole by borehole (e.g. in the Borehole Geology database) or in cross section panels in GSI3D/Groundhog software. The interpretation of boreholes is thus a substantial cost, and a major rate-limiting step, in geological model development. In order to utilise the new borehole data available and ensure models can be efficiently updated when new records are received, innovative technological approaches are needed to capture lithological and stratigraphic interpretations of boreholes. The Geological Survey of the Netherlands has developed methods that use python scripts to semi-automate this process base on a high-level stratigraphy (Stafleu *et al.* 2019),

.

Some pathways for how this can be achieved include:

- Development of workflows for visualising and interpreting clouds of boreholes
- Integrate 3D interpretation borehole and rules-based interpretation semi-automated interpterion borehole into model building to limit the time spent creating fences of cross-sections.
- Prioritise key erosional surfaces, which can be identified in boreholes relatively easily, rather than full stratigraphic successions – this is particularly important in complex superficial sequences where lithological units may be hard to correlate laterally,
- Create outcrop/subcrop maps as part of the borehole interpretation process to aid large area interpretation.
- Investigate ways to semi-automate the borehole coding process based on stratigraphic rules. Investigate options to repurpose existing tools to do this, e.g. Python codes, GeoVisionary, Groundhog.

There is a circular link between models and input datasets (Figure 19); by constructing a geologically sound 3D model from the borehole dataset a 3D stratigraphic understanding of those boreholes is also generated which is also critical for providing confidence in the modelled surfaces.

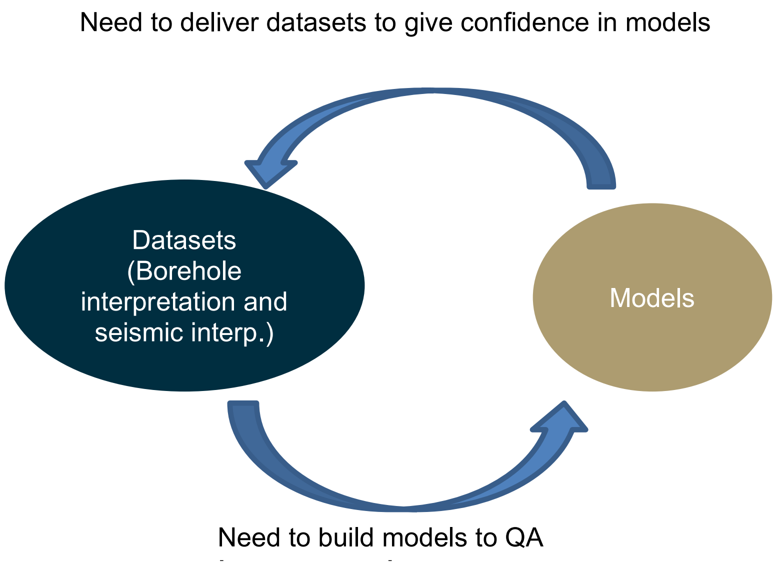


Figure 19 The circular link between models and between models and borehole datasets

6.4 TRIALLING DIFFERENT SOFTWARE

The ongoing development of modelling software, and emergence of new modelling tools, is providing both the opportunity and the need to evolve BGS modelling workflows. LOOP (https://loop3d.github.io/) and Gempy (https://www.gempy.org/) provide open-source options for implicit 3D geological modelling. Also, the increasing use of Leapfrog 3D in the Engineering Geology sector.

Equally the evolution the way BGS has developed 3D modelling software to calculates surfaces from direct triangulation (GSI3D) to interpolation (Groundhog) means that workflows could potentially be adapted. The following tests could be undertaken to assess opportunities to adapt and evolve key workflows for bedrock and superficial modelling:

- Build test LOOP models (using map data) in areas where we already have existing urban bedrock models created from borehole data for comparison;

- Migration of an existing GSI3D superficial model to Groundhog and test model interpolation with varying amounts of input borehole and cross-section data;
- Build external collaboration, for example with Florian Wellmann at Aachen University, to develop capability in the use of Gempy
- Make more used Stochastic lithological modelling and simplify the number of Lithostratigraphic units based on the geology observed in boreholes and not just following the stratigraphy on the map.

6.5 MODEL DELIVERY

BGS has trialled a range of delivery approaches for 3D model data since c. 2010, including delivery of National Capability models for GB, and international projects. Similar trials have been undertaken by other geological surveys, such as the Geological Survey of the Netherlands. Lessons from this experience highlight that effective engagement with diverse urban stakeholder communities requires delivery of relevant applied or value-added outcomes from geological models, rather than the 3D model itself.

Effective uses of models in delivering impact for stakeholders include using the model to update geological maps and create 'hybrid' maps that include additional depth information (e.g. include depth contours for key units or use of transparencies so that concealed units can be seen), as well as delivering depth and thickness grids. Such outputs are accessible to a wide range of stakeholders and can be more readily integrated into their existing workflows. Thus:

- Urban models need a multi-platform delivery strategy (e.g. the same model made available in a range of media);
- The delivery strategy for a model needs to be outlined in the initial planning phase of the project to ensure appropriate software is used (see further discussion below), and suitable QA and development activities are completed for model release;

It is important to note that currently BGS cannot commercially charge for models built using SKUA-GOCAD or Petrel, which can also mean that a publication strategy must be agreed with all parties involved at the start of the project.

6.6 UNCERTAINTY

The accuracy and uncertainty surrounding geological models is one of the issues that often comes up with stakeholders. Wellmann *et al.* (2010) identify three types of uncertainty in subsurface prediction:

Type 1 (error, bias, and imprecision): uncertainty in all types of raw data that are used for modelling, e.g. the position of a mapped formation boundary or the orientation of a structure

Type 2 (stochasticity, and inherent randomness): this commonly appears as the uncertainty in interpolation between (and extrapolation from) known data points

Type 3 (imprecise knowledge): applies to incomplete and imprecise knowledge of structural complexity, general conceptual ambiguities and the need for generalisations

Wellmann *et al.* (2010) advocate using information entropy to quantify this. The Netherlands Organisation for Applied Scientific Research (TNO) have tried this method but found most useful for helping geologists understand where more boreholes would have the greatest impact in improving the model, it is less useful for explaining uncertainty to stakeholders. Instead a method like the R-index, defined by Dematteis & Soldo (2015) for use in tunnelling contexts (, could be used. The R-index is a probabilistic procedure for systematically assessing the reliability of input data to a planning and design process.

7 Recommendations

Urban geology

1. Any future 3D urban geology characterisation and modelling should initially be focused on the towns and cities of Greater Manchester, Liverpool, Newcastle(-Gateshead), Leeds, Sheffield and Milton Keynes, with consideration given to Bristol, Nottingham, Stoke-on-Trent and Edinburgh.

2. Characterisation of till deposits, river terrace deposits and the Carboniferous are high priority for urban geological NC research due to their relative prevalence beneath urban areas, and the nature and complexity of the geology

Interpreted 3D urban geology elements

3. To support the development of 3D urban geology/ground models by the external user community, BGS's 3D geology NC-activities should focus primarily on the generation and delivery of interpreted model elements, such as coded boreholes, subcrop maps, 3D conceptual facies and lithology diagrams. The development of full 3D urban geology models being a secondary aim and aligned to priority areas indicated in recommendation 1.

4. Develop methods it improves borehole coding for high priority urban centres needs to be undertaken as a strategic deliverable. This should be done using a defined stratigraphic framework which is based on what can be determined from boreholes and not was is seen from surface mapping. This will form the basis of improved understanding of the 3D urban subsurface, rather than *ad hoc* coding of boreholes in isolation. Alongside this Shallow Borehole Stratigraphic Reports could be created which detail the stratigraphy at the urban scale and include facies diagrams, maps and statistical plots to explain the geological variability in an accessible form. The reports should include a list of borehole markers as a data appendix.
    - Tier 1 - Greater Manchester; Newcastle; Leeds; Sheffield; Milton Keynes
        - Estimated number of boreholes to be coded: 14,000.
        - Estimated cost for coding the boreholes: £27 k/yr for 3 years @cash (based on B6-geologist coding 200 BHs/week)
    - Tier 2 – Bristol; Nottingham; Stoke-on-Trent
        - Estimated number of boreholes to be coded: 1,800
          Estimated cost for coding the boreholes: £10k total @cash (based on B6-geologist coding 200 BHs/week)
5. Innovation funding proposals submitted to BGS-Innovation and UKRI to:
    a. Investigate (semi)-automated processes for borehole coding.
    b. Develop workflows for visualising and interpreting clouds of boreholes.

3D modelling approaches

6. Modelling approaches must be suitable for the dominant urban geological units – complex, faulted bedrock (Carboniferous), and mixed Quaternary lithologies (till).

7. Explore options for developing more efficient workflows for urban geological modelling using existing software, such as Groundhog, (e.g. only using envelopes and boreholes rather than drawing cross sections).

8. Bench-test the LOOP modelling software to model bedrock in priority urban areas. This may require the digitisation of structural data such as dip and strike readings. The results should be compared to existing borehole interpretations.

9. Trial methods to characterise uncertainty in geological predictions and work with stakeholders to understand how best to communicate uncertainty information.

10. Explore opportunities to move to implicit modelling approaches for Quaternary deposits (e.g. using Leapfrog) which will enable quicker model update and allow complex deposits e.g. tills to be modelled more effectively.

References

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

BIDARMAGHZ, A., CHOUDRHARY, R., SOGA, K., KESSLER, H., TERRINGTON, R. L., THORPE, S., 2019. Influence of geology and hydrogeology on heat rejection from residential basements in urban areas. *Tunnelling and Underground Space Technology*, Vol 92, 103068. http://dx.doi.org/10.1016/j.tust.2019.103068

BRICKER, S. TERRINGTON, R. DOBBS, M, KEARSEY, T. BURKE, H. ANRHARDT, R. THORPE, S. 2021. Urban Geoscience Report - The value of geoscience data, information and knowledge for transport and linear infrastructure projects. *British Geological Survey Open Report*, OR/21/065. 71pp

DEMATTEIS, A. AND SOLDO, L., 2015. The geological and geotechnical design model in tunnel design: estimation of its reliability through the R-Index. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, *9*(4), pp.250-260.

EVANS, D., STEPHENSON, M., AND SHAW, R., 2009. The present and future of 'land' below ground. *Land Use Policy* Vol 26, Supplement 1, December 2009, pp S303-S316. https://www.sciencedirect.com/science/article/abs/pii/S0264837709001409?via%3Dihub

GATES, J., DABSON, O.J.N., FITZGERALD, R.J., FREE, M., GILSON, B., MANNING, J., HOSKER, R., GAKIS, A., CABRERO, P., ENTWISLE, D., MCARDLE, G., CHAMFRAY, J., MILES, S.R., MORIN, G., PEERSMANN, M.R. AND VAN DER MEULEN, M.J., 2021. The Economic Case for Establishing Subsurface Ground Conditions and the Use of Geological Models. In Applied Multidimensional Geological Modeling (eds A. Keith Turner, H. Kessler and M. J van der Meulen). https://doi.org/10.1002/9781119163091.ch4

JONES, L.; HULBERT, A., 2017. User guide for the Shrink-Swell 3D (GeoSure Extra) dataset v1.0. Nottingham, UK, British Geological Survey, 14pp. (OR/16/043) (Unpublished).

KEARSEY, T., WILLIAMS, J., FINLAYSON, A., WILLIAMSON, P., DOBBS, M., MARCHANT, B., KINGDON, A., AND CAMPBELL, S., 2014. *Lithostratigraphy does not always equal lithology: lessons learned in communicating uncertainty from stochastic modelling glacial and post glacial deposits in Glasgow, UK*. Poster for EGU General Assembly 2014, Vienna, Austria 28th April-2nd May 2014. http://nora.nerc.ac.uk/id/eprint/507483/.

KEARSEY, TIMOTHY; WILLIAMS, JOHN; FINLAYSON, ANDREW; WILLIAMSON, PAUL; DOBBS, MARCUS; MARCHANT, BENJAMIN; KINGDON, ANDREW ; CAMPBELL, DIARMAD. 2015 Testing the application and limitation of stochastic simulations to predict the lithology of glacial and fluvial deposits in Central Glasgow, UK. Engineering Geology, 187. 98 - 112. https://doi.org/10.1016/j.enggeo.2014.12.017

KEARSEY, T.I.; WHITBREAD, K.; ARKLEY, S.L.B.; FINLAYSON, A.; MONAGHAN, A.A.; MCLEAN, W.S.; TERRINGTON, R.L.; CALLAGHAN, E.A.; MILLWARD, D.; CAMPBELL, S.D.G., 2019. Creation and delivery of a complex 3D geological survey for the Glasgow area and its application to urban geology. Earth and Environmental Science Transactions of The Royal Society of Edinburgh, 108 (2-3). 123-140.

LAWLEY, R. AND GARCIA-BAJO, M., 2010. The National Superficial Deposit Thickness Model (version 5). BGS Open Report no. OR/09/049. http://nora.nerc.ac.uk/id/eprint/8279/

MATHERS, S.J.; BURKE, H.F.; TERRINGTON, R.L.; THORPE, S.; DEARDEN, R.A.; WILLIAMSON, J.P.; FORD, J.R.. 2014 A geological model of London and the Thames Valley, southeast England. Proceedings of the Geologists' Association, 125 (4). 373-382. https://doi.org/10.1016/j.pgeola.2014.09.001

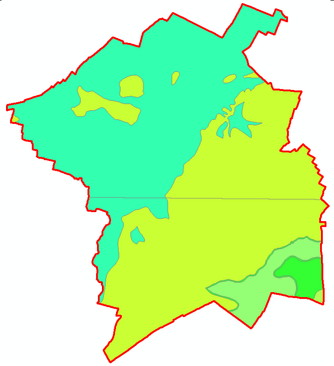
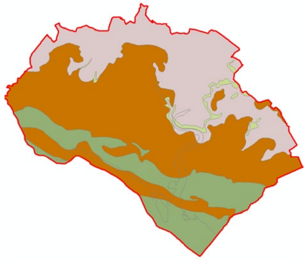
PALAMAKUMBURA, R., 2018. A new palaeogeographic model for the post-glacial marine and estuarine sediments of the Firth of the Forth, Scotland. Nottingham, UK, British Geological Survey, 50pp. (OR/18/016) (Unpublished)

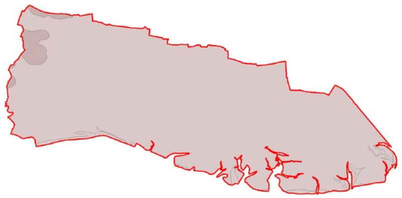
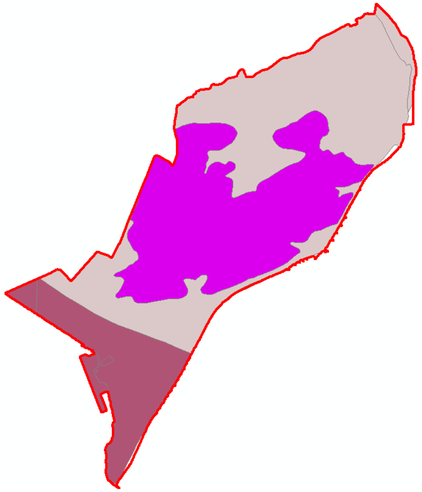
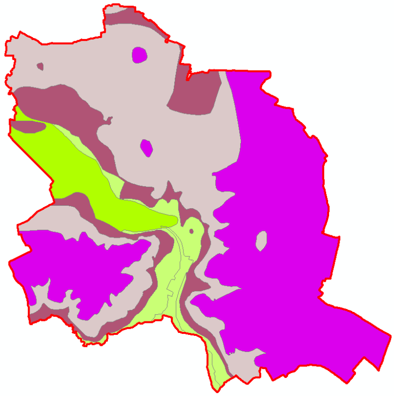
SCHOKKER, J.; SANDERSEN, P.; DE BEER, H.; ERIKSSON, I.; KALLIO, H.; KEARSEY, T.; PFLEIDERER, S.; SEITHER, A., 2017. 3D urban subsurface modelling and visualisation : a review of good practices and techniques to ensure optimal use of geological information in urban planning. COST European Cooperation in Science and Technology, 100pp.

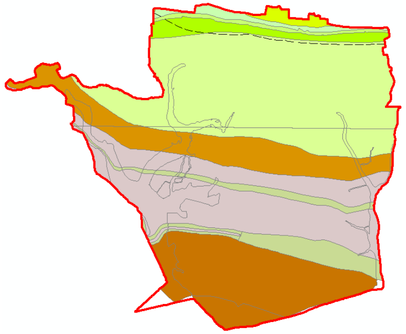
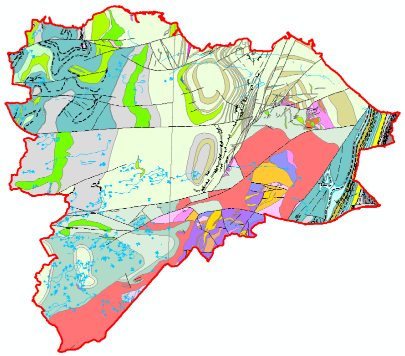
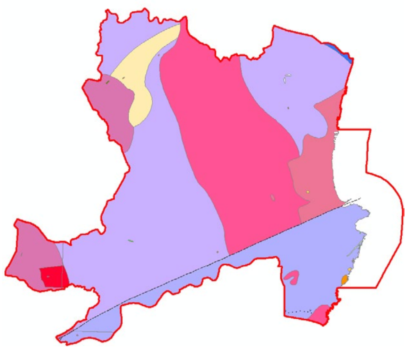
STAFLEU, J., VAN DER MEULEN, M.J., GUNNINK, J.L., MALJERS, D., HUMMELMAN, J., BUSSCHERS, F.S., SCHOKKER, J., VERNES, R.W., DOORNENBAL, H., DEN DULK, M. AND TEN VEEN, J.H., 2019. Systematic 3D subsurface mapping in the Netherlands. Synopsis of current three-dimensional geological mapping and modelling in geological survey organizations. Alberta Energy Regulator/Alberta Geological Survey, AER/AGS Special Report, 112, pp.179-190.

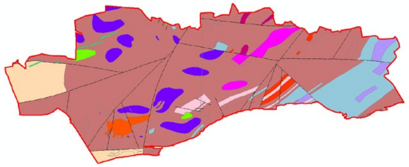
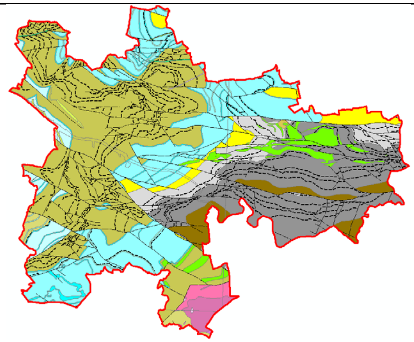
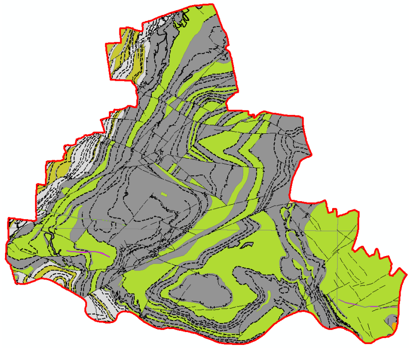
WATSON, C., JENSEN, N-J, RYŻYŃSKI, G., MAJER, K. AND HANSEN M., 2017. Data Acquisition & Management. COST European Cooperation in Science and Technology, TU1206-WG2.2-003. 68WELLMANN, J.F., HOROWITZ, F.G., SCHILL, E. AND REGENAUER-LIEB, K., 2010. Towards incorporating uncertainty of structural data in 3D geological inversion. Tectonophysics, 490(3-4), pp.141-151.

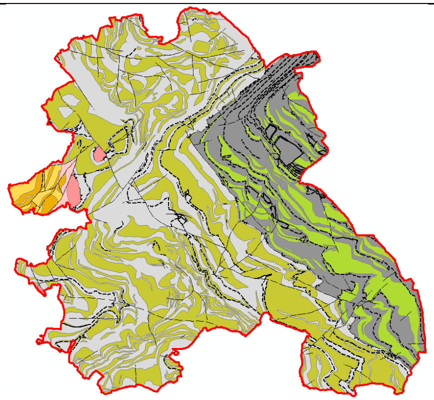
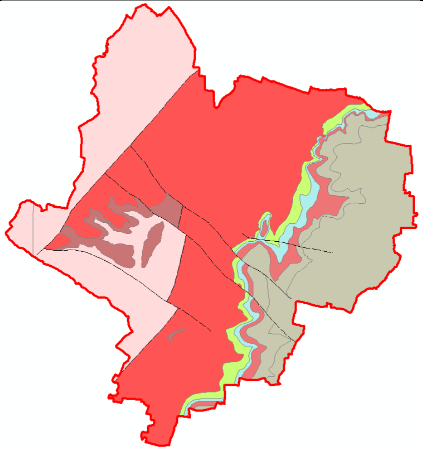
Appendix 1 Summary of bedrock geology for each town and city in the study

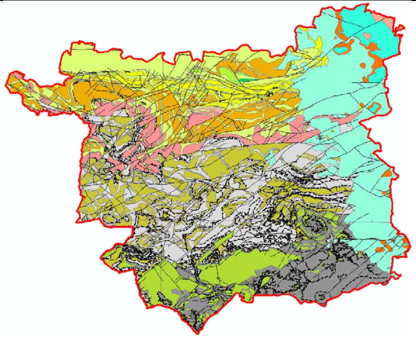
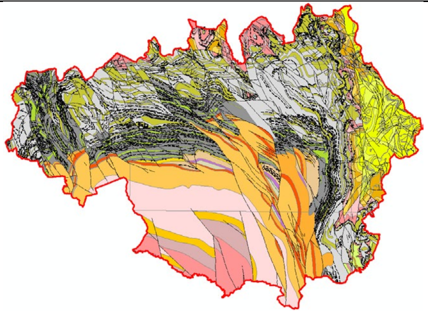
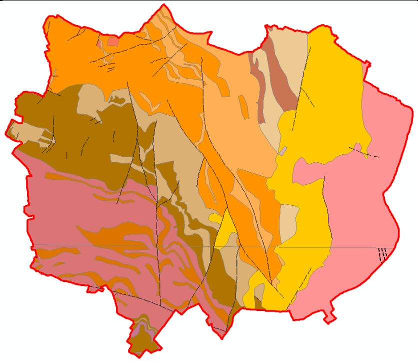
	1:50 000 scale bedrock geology map (town/city outlined in red)	Area (km^2)	No. named mapped bedrock units	Age of mapped bedrock	Bedrock lithologies	Dominant unit by area	Structural data available
Cambridge District		40.7	7	100% Cretaceous	Chalk and mudstone	Gault Fm: Early Cretaceous mudstone	Yes (but northern half only)
City of Southampton		56.39	8	100% Palaeogene	Clay, silt and sand	Wittering Fm: Palaeogene clay and sand	No

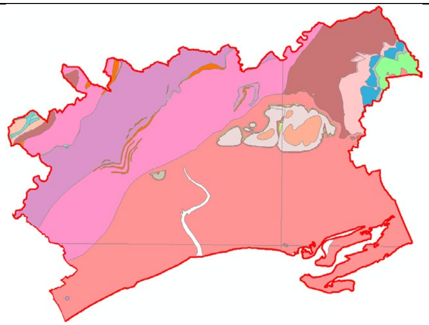
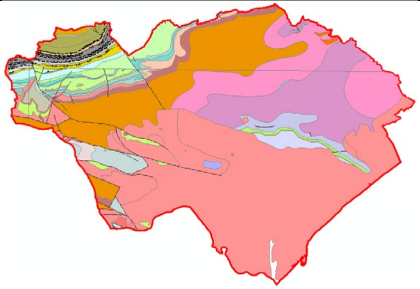
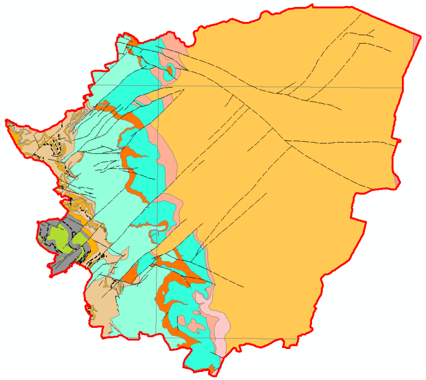
Southend-on-Sea		67.96	2	100% Palaeogene	Clay	London Clay Fm	No
Felixtowe		17.44	3	38% Neogene, 62%Palaeogene	Clay, silt and sand	Thames Group (London Clay Fm & Harwich Fm undivided)	No
Ipswich District		40.3	5	42% Neogene, 46% Palaeogene, 13% Cretaceous	Clay, silt, sand and chalk	Red Crag Fm: Neogene sand	No

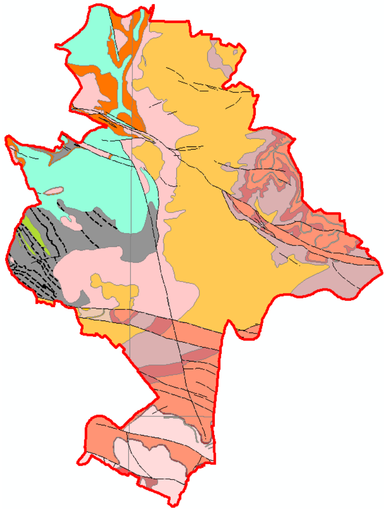
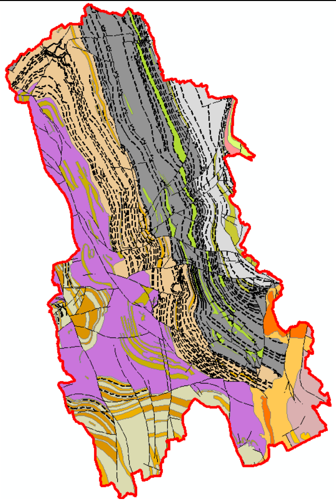
City of Portsmouth		60.14	14	58% Palaeogene, 42% Cretaceous	Clay, silt, sand and chalk	Lewes Nodular/ Seaford/ Newhaven/ Culver Chalk Fms undivided	Yes
City of Edinburgh		272.88	66	82% Carboniferous, 11% Devonian, 7%, Silurian	Sandstone, siltstone, mudstone, limestone, coal, volcanic rocks	Strathclyde Group - West Lothian Oil-Shale Fm, Gullane Fm, Arthur's Seat Volcanic Fm, Ballagan Fm	Yes
Aberdeen City		205.56	14	0.1% Carboniferous, 14% Devonian, 9% Slurian, 78% Ordovician	Psammite & semipelite, granite, conglomerate & sandstone, granodiorite, peridotite	Aberdeen Fm	Yes

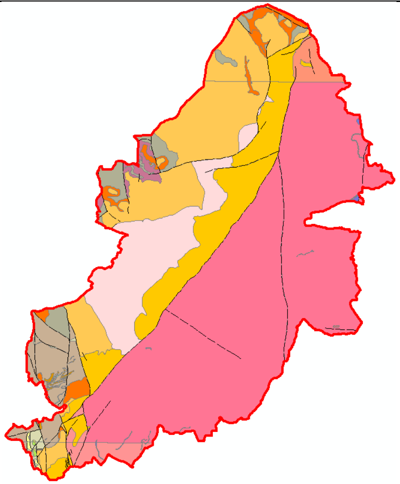
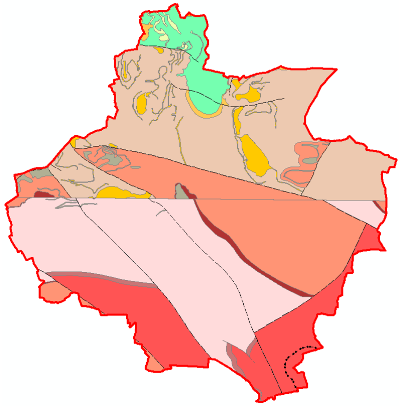
Dundee City		62.41	8	0.2% Carboniferous, 89% Devonian; 11% Silurian	Sandstone, andesite, microdiorite, basalt, microgabbro, tuff	Dundee Flagstone Fm	Yes
Glasgow City		176.36	33	100% Carboniferous	Coal Measures (mudstone, siltstone, sandstone, coal, seatearth), limestone, basalt, microgabbro intrusions	Limestone Coal Fm: Devonian limestone, mudstone, siltstone sandstone, coal	Yes
Newcastle Upon Tyne District		115.10	11	100% Carboniferous	Coal Measures (mudstone, siltstone, sandstone, coal, seatearth), microgabbro intrusions	Pennine Coal Measures Group	No

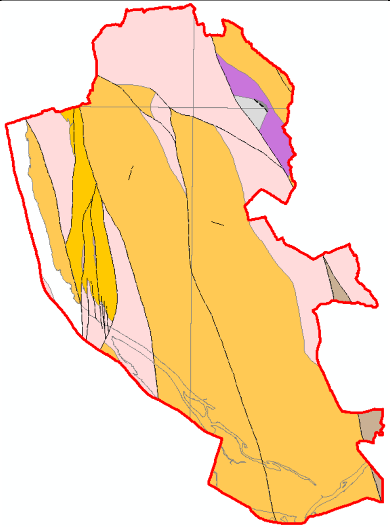
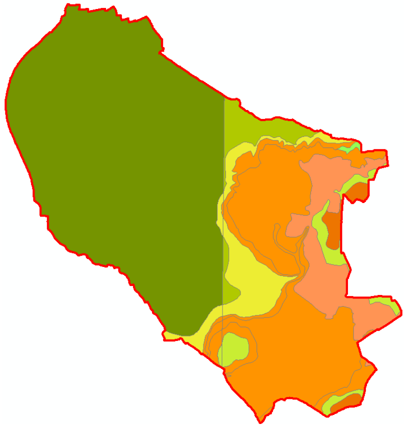
Sheffield city		126.87	17	100% Carboniferous	Coal Measures (mudstone, siltstone, sandstone, coal, seatearth)	Pennine Coal Measures Group	No
City of Leicester		73.34	8	100% Triassic	Mudstone, sandstone, limestone	Branscombe Mudstone Fm (Mercia Mudstone Group)	No
City of Bristol		235.44	35	13% Jurassic, 64% Triassic, 22% Carboniferous, 1% Devonian	Mudstone, limestone, sandstone	Mercia Mudstone Group	No

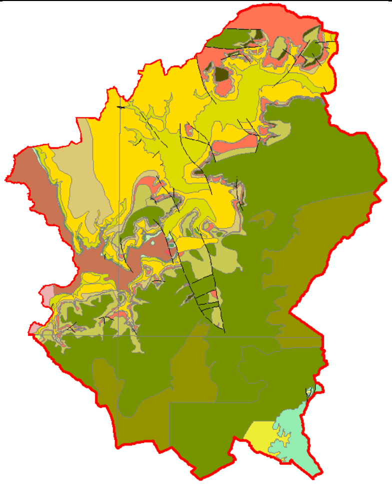
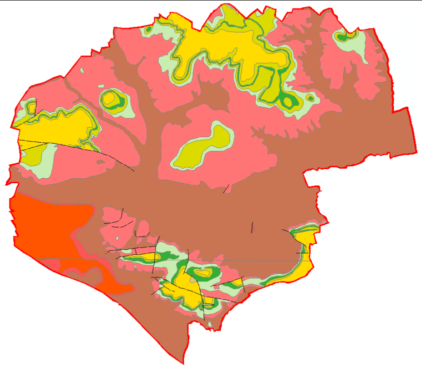
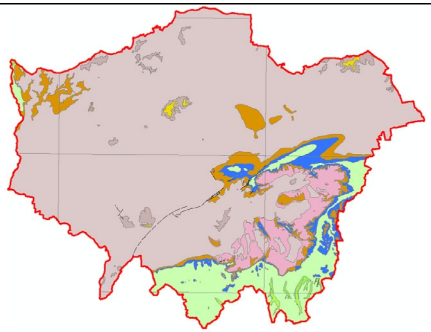
Leeds District		555.71	47	21% Permian, 79% Carboniferous	Coal Measures (mudstone, siltstone, sandstone, coal, seatearth) dolostone, sandstone	Pennine Coal Measures Group	No
Greater Manchester		1275.98	67	28% Triassic, 5% Permian, 67% Carboniferous	Coal Measures (mudstone, siltstone, sandstone, coal, seatearth), sandstone, mudstone	Pennine Coal Measures Group	South only
Coventry District		98.64	9	29% Triassic, 1% Permian, 70% Carboniferous	Predominantly sandstone, some mudstones	Salop Formation: sandstone	No

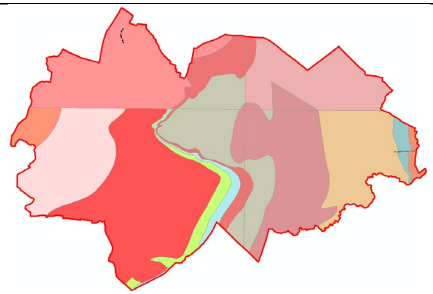
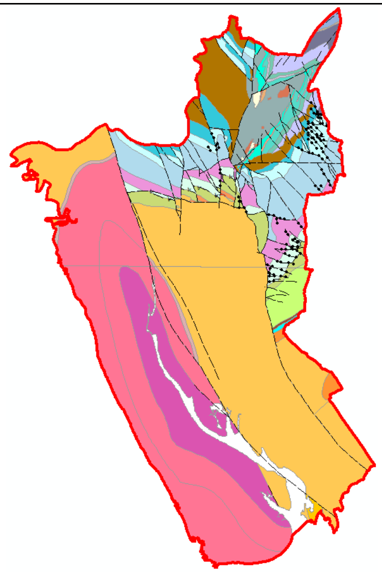
Casnewydd - Newport		217.52	21	3% Jurassic, 91% Triassic, 6% Carboniferous	Mudstone, sandstone, limestone	Mercia Mudstone Group: mudstone	Yes
Caerdydd - Cardiff		149.45	41	4% Jurassic; 20% Triassic, 22% Carboniferous, 30% Devonian, 25% Silurian	Mudstone, sandstone, Coal Measures (mudstone, siltstone, sandstone, coal, seatearth)	Mercia Mudstone Group: mudstone	No
Doncaster District		568.54	16	46% Triassic, 45% Permian,9% Carboniferous	Sandstone, dolostone, Coal Measures (mudstone, siltstone, sandstone, coal, seatearth)	Sherwood Sandstone Group: sandstone	Yes

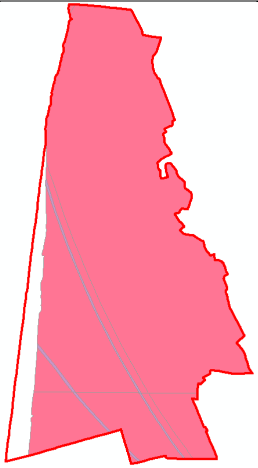
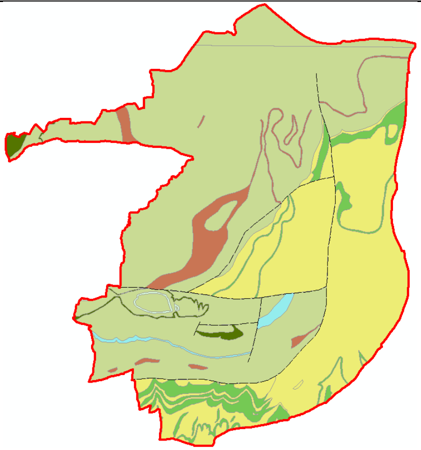
City of Nottingham		74.61	12	62% Triassic, 30% Permian, 8% Carboniferous	Sandstone, mudstone, dolostone, Coal Measures (mudstone, siltstone, sandstone, coal, seatearth)	Sherwood Sandstone Group: sandstone	No
City of Stoke-on-Trent		93.45	15	7% Triassic, 93% Carboniferous	Coal Measures (mudstone, siltstone, sandstone, coal, seatearth), mudstone, sandstone	Pennine Coal Measures Group: mudstone, siltstone, sandstone, coal, seatearth	No

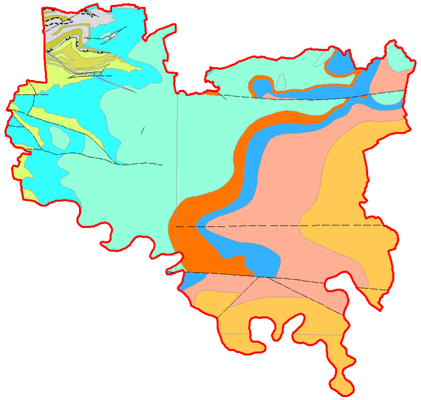
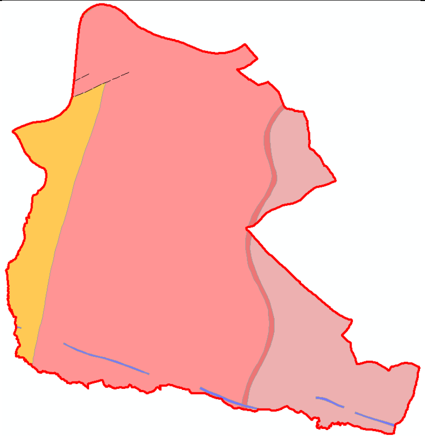
Birmingham District		267.79	17	90% Triassic, 2% Permian, 8% Carboniferous, 0.04% Silurian, 0.10% Ordovician	Mudstone, sandstone	Sidmouth Mudstone Formation (Mercia Mudstone Group): mudstone	No
City of Derby		78.03	11	95% Jurassic, 5% Carboniferous	Predominantly mudstone, some sandstone	Mercia Mudstone Group: mudstone	No

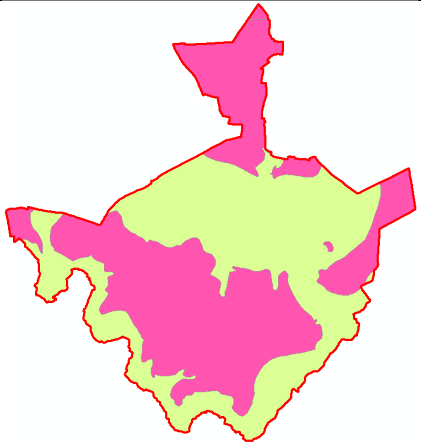
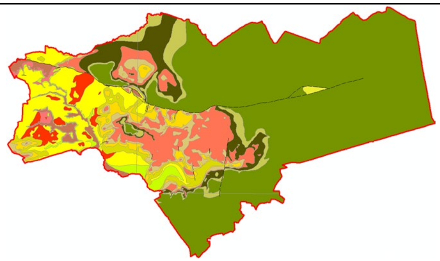
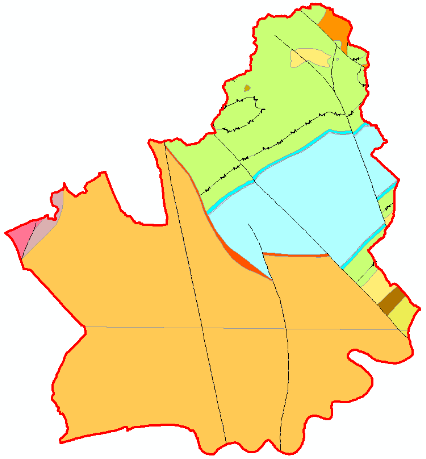
Liverpool District		133.53	8	97% Triassic, 3% Carboniferous	Predominantly sandstone, some mudstone and Coal Measures ((mudstone, siltstone, sandstone, coal, seatearth)	Chester Formation (Sherwood Sandstone Group): sandstone	Yes
Oxford District		45.60	10	100% Cretaceous	Predominantly mudstone, some sandstone, limestone	Oxford Clay Formation & West Walton Formation undivided: mudstone	No

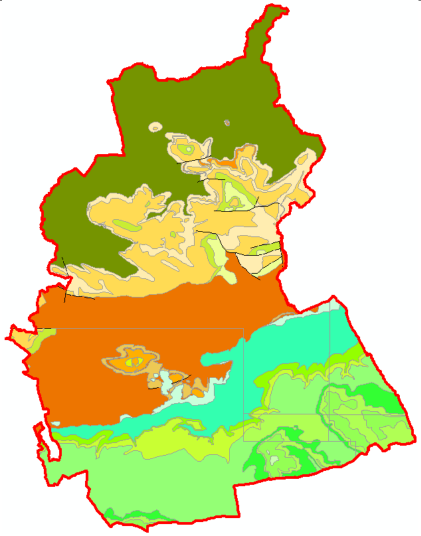
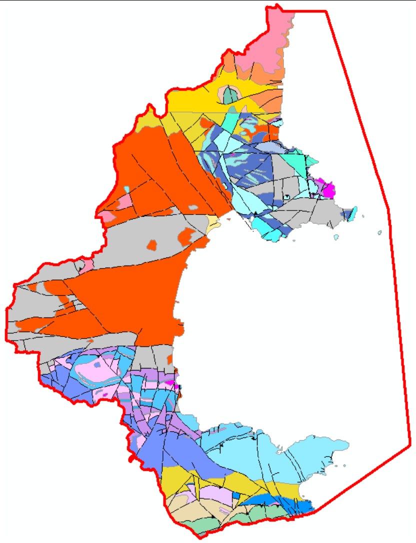
Milton Keynes		308.63	20	2% Cretaceous, 98% Jurassic	Mudstone, limestone	Oxford Clay Formation: mudstone	Yes
Northampton		80.77	9	85% Jurassic, 15% Triassic	Mudstone, sandstone, limestone	Whitby Mudstone Formation: mudstone	Yes
Greater London		1594.69	11	89% Palaeogene, 11% Cretaceous	Clay, sand, sand & gravel, chalk	London Clay Formation: clay	No

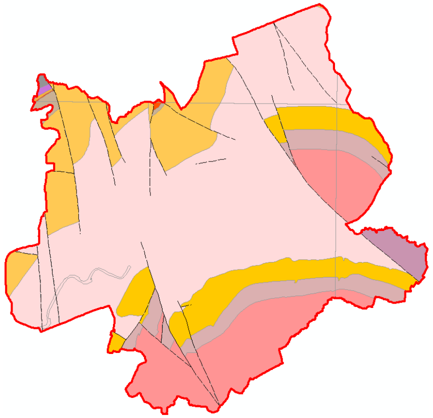
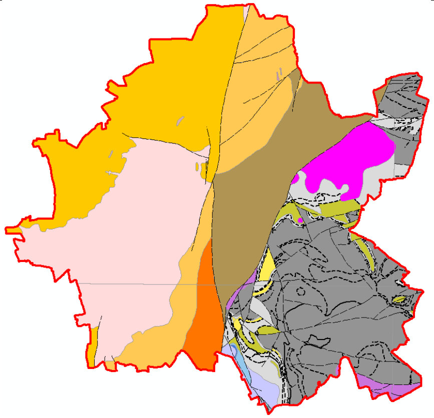
Newark on Trent*		36.21	14		Predominantly mudstone, minor limestones	Scunthorpe Mudstone Formation (and subdivisions thereof): mudstone	No
Barrow-in-Furness*		132.07	31		Sandstone, mudstone, halite, limestone, calcarenite, volcanic rocks	St Bees Sandstone Member (Sherwood Sandstone Group): sandstone	No

Blackpool*		43.15	5		Mudstone	Kirkham Mudstone Member: mudstone	Yes
Crawley District*		44.97	3		Mudstone, sand, minor sandstone and limestone	Weald Clay Formation: mudstone	Yes

Darlington*		197.47	10		Dolostone, calcareous mudstone, sandstone, Coal Measures	Ford Formation: dolostone	No
Middlesbrough*		54.55	5		Primarily mudstone, some sandstone	Mercia Mudstone Group: mnudstone	No

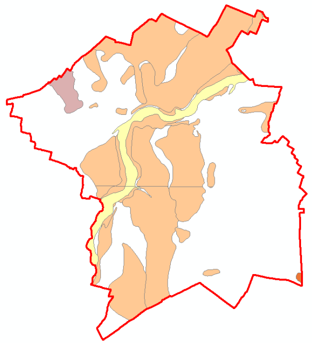
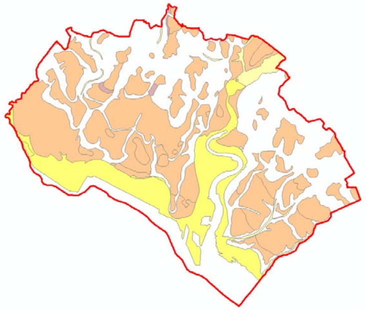
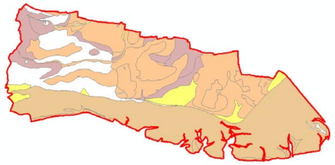
Norwich District*		39.16	3		Chalk, sand and gravel	Lewes Nodular/ Seaford/ Newhaven/ Culver Chalk Formations undivided: chalk	Yes
City of Peterborough*		343.43	13		Mudstone, limestone, sandstone	Oxford Clay Formation: mudstone	Partial coverage
Preston District*		142.94	14		Sandstone, mudstone, minor limestone	Sherwood Sandstone Group: sandstone	No

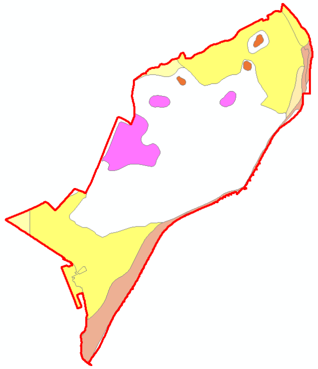
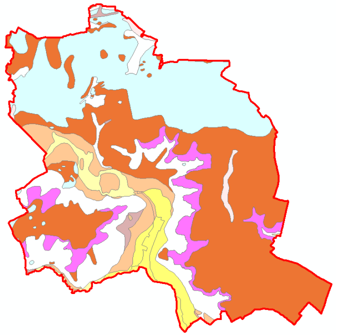
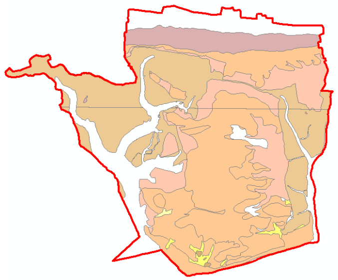
Swindon*		230.09	22		Mudstone, chalk, limestone, sandstone	Oxford Clay Formation: mudstone	Yes
Torbay*		119.45	27		Sandstone & breccia, limestone, mudstone, volcanic rocks	Torre Breccia Formation: interbedded breccia and sandstone	No

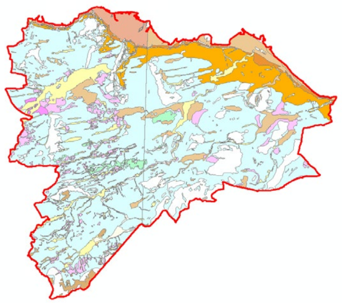
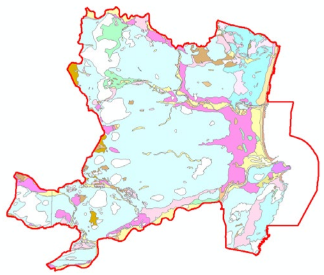
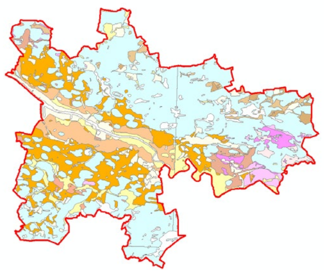
Warrington*		182.38	11		Predominantly sandstone, some mudstone	Wilmslow Sandstone Formation (Sherwood Sandstone Group: sandstone	Yes
City of Wolverhampton*		39.44	19		Sandstone, Coal Measures (mudstone, siltstone, sandstone, coal, seatearth), breccia igneous rocks	Pennine Coal Measures Group: mudstone, siltstone, sandstone, coal, seatearth	No

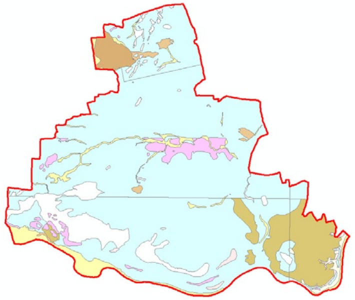
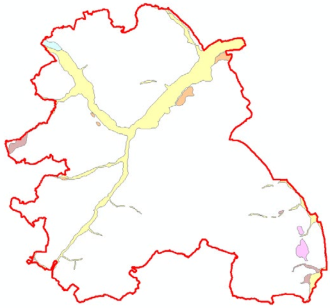
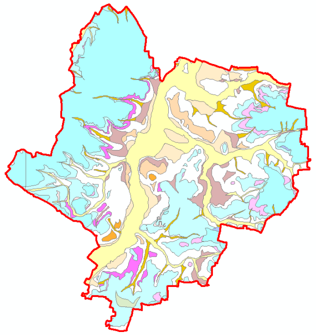
*Cohort 1 town

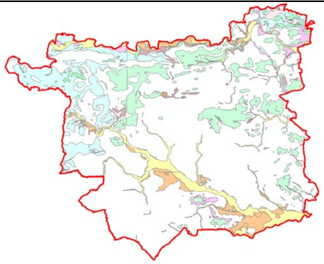
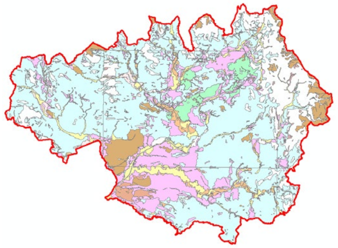
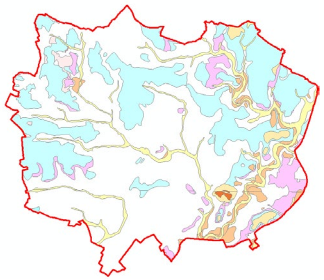
Appendix 2 Summary of superficial deposits for each town and city in the study

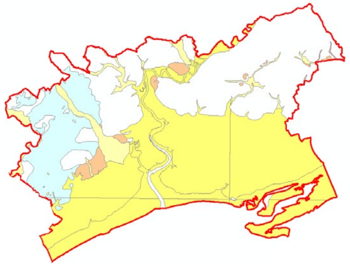
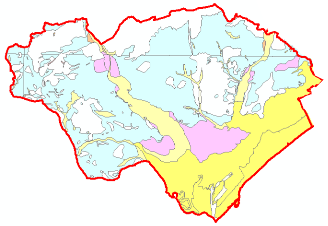
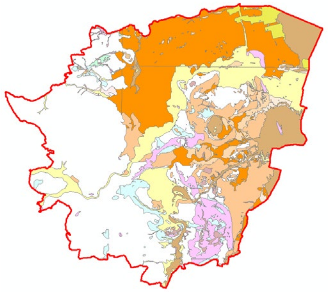
	1:50 000 scale superficial geology map (town/city outlined in red, white areas indicate bedrock at surface)	Area (km^2)	Superficial coverage (km^2)	No. mapped Quaternary units	Nature of deposition	Dominant unit by area
Cambridge District		40.7	18.55 (46%)	8	Glacigenic, fluvial, slope deposits	Largely bedrock at surface, main Quaternary unit is river terrace deposits
City of Southampton		56.39	31.81 (56%)	16	Fluvial, coastal, slope deposits	River terrace deposits
Southend-on-Sea		67.96	59.27 (87%)	12	Glacigenic, fluvial, coastal, aeolian, slope deposits	Beach and tidal flat deposits (undifferentiated)

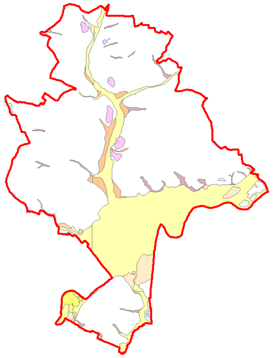
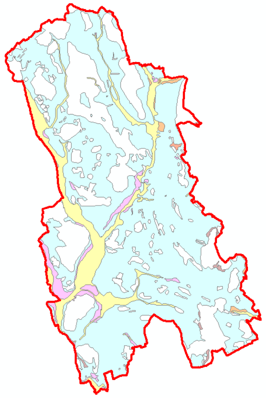
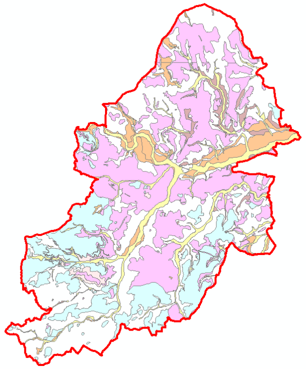
Felixtowe		17.44	8.53 (49%)	7	Glacigenic, fluvial, coastal, aeolian	Largely bedrock at surface, dominant Quaternary unit is tidal flat deposits
Ipswich District		40.3	34.33 (85%)	9	Glacigenic, fluvial, coastal, slope deposits	Glacial sand & gravel
City of Portsmouth		60.14	49.62 (83%)	9	Fluvial, coastal, slope deposits,	Marine and beach/tidal flat deposits

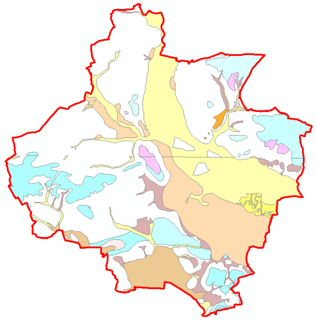
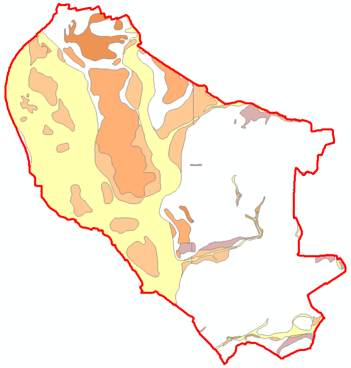
City of Edinburgh		272.88	235.79 (86%)	20	Glacigenic, fluvial, coastal, aeolian	Till, Devensian
Aberdeen City		205.56	165.76 (80.64%)	22	Glacigenic, fluvial, coastal, aeolian, slope deposits	Till, Devensian
Dundee City		62.41	58.93 (94%)	11	Glacigenic, fluvial, coastal, aeolian	Till, Devensian
Glasgow City		176.36	166.13 (94%)	20	Glacigenic, fluvial, coastal	Till, Devensian

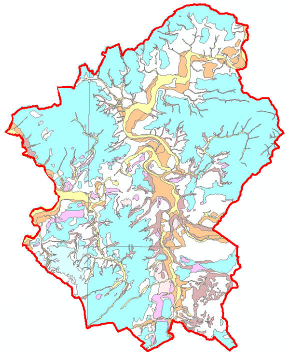
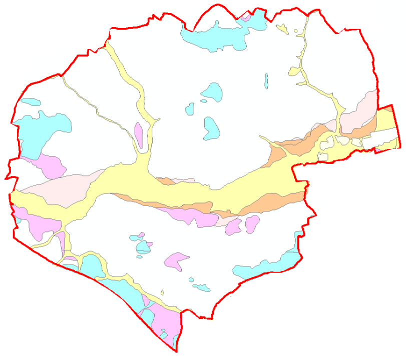
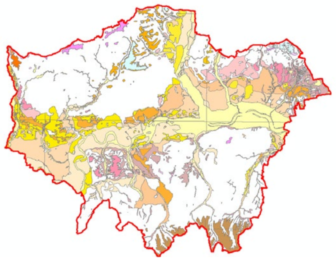
Newcastle Upon Tyne District		115.10	106.69 (93%)	10	Glacigenic, fluvial, coastal	Till, Devensian
Sheffield city		126.87	12.43 (10%)	6	Glacigenic, fluvial, slope deposits	Mainly bedrock at surface, dominant Quaternary unit is alluvium
City of Leicester		73.34	56.27 (77%)	14	Glacigenic, fluvial, slope deposits	Till, Mid Pleistocene

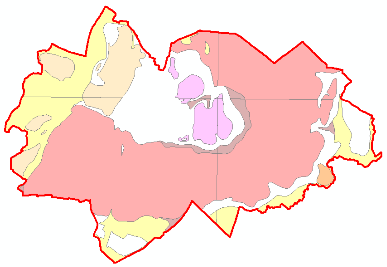
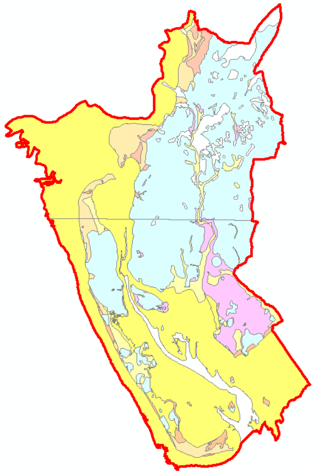
City of Bristol		235.44	29.98 (13%)	5	Fluvial, coastal, slope deposits	Mainly bedrock at surface, main Quaternary unit is tidal flat deposits
Leeds District		555.71	178.96 (32%)	20	Glacigenic, fluvial, slope deposits	Largely bedrock at surface, the dominant Quaternary unit is till, Mid Pleistocene/Devensian
Greater Manchester		1275.98	1067.27 (84%)	22	Glacigenic, fluvial, slope deposits, aeolian	Till, Devensian
Coventry District		98.64	43.34 (44%)	14	Glacigenic, fluvial	Till, Mid Pleistocene

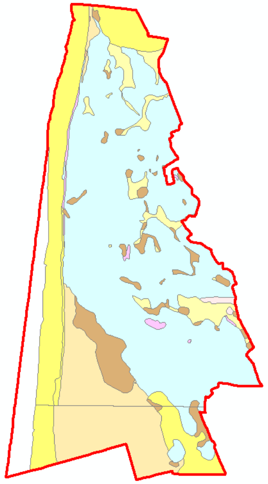
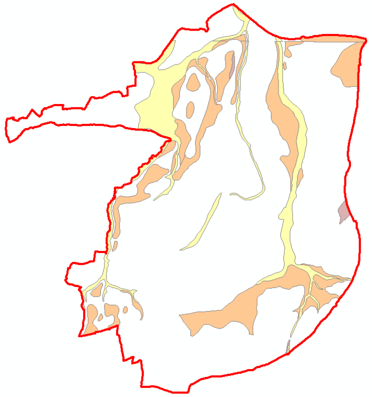
Casnewydd - Newport		217.52	140.99 (65%)	8	Glacigenic, fluvial, slope deposits, coastal	Large areas of bedrock at surface, dominant Quaternary unit is tidal flat deposits
Caerdydd - Cardiff		149.45	113.59 (76%)	11	Glacigenic, fluvial, slope deposits, coastal	Till, Devensian
Doncaster District		568.54	357.87 (63%)	19	Glacigenic, fluvial, slope deposits, aeolian, peat	Mainly bedrock at surface in the west. Dominant Quaternary unit is glaciolacustrine deposits

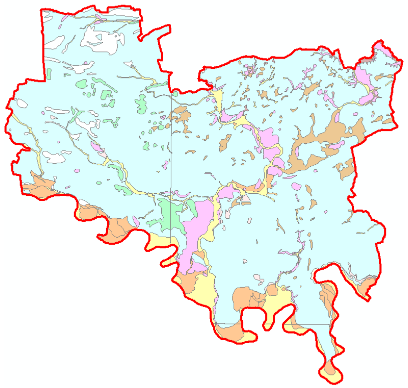
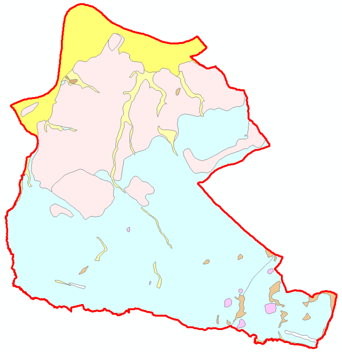
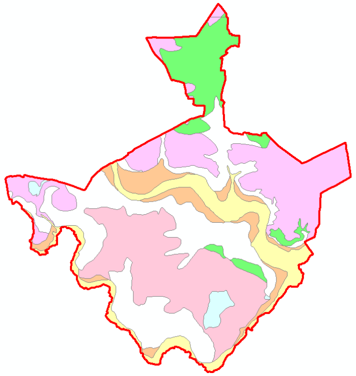
City of Nottingham		74.61	20.66 (28%)	14	Glacigenic, fluvial, slope deposits	Predominantly bedrock at surface, dominant Quaternary unit is alluvium
City of Stoke-on-Trent		93.45	67.14 (72%)	7	Glacigenic, fluvial, slope deposits	Till, Devensian
Birmingham District		267.79	166.51 (62.18%)	13	Glacigenic, fluvial, slope deposits	Glaciofluvial deposits (Mid Pleistocene)

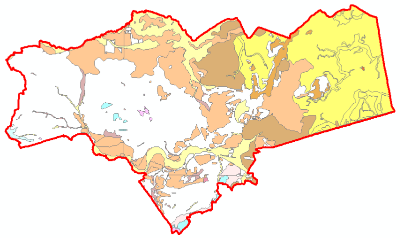
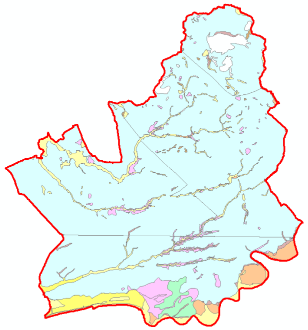
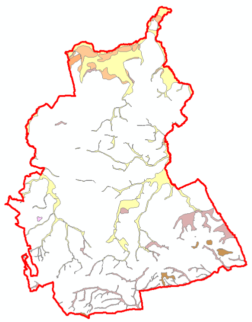
City of Derby		78.03	41.57 (53%)	14	Glacigenic, fluvial, slope deposits,	Largely bedrock at surface, but the main Quaternary unit is alluvium
Liverpool District		133.53	96.42 (72%)	6	Glacigenic, aeolian, fluvial, coastal	Till, Devensian
Oxford District		45.60	23.05 (51%)	8	Fluvial, slope deposits	Largely bedrock at surface, dominant Quaternary unit is alluvium

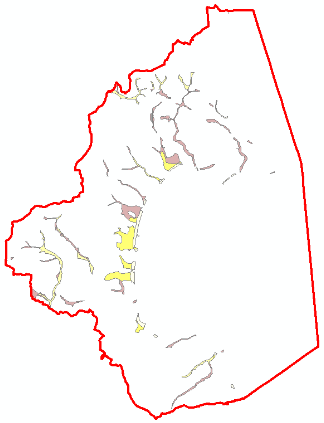
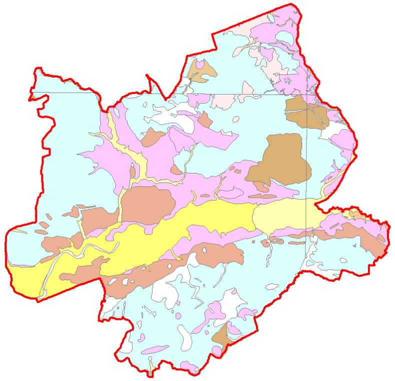
Milton Keynes		308.63	217.68 (71%)	16	Glacigenic, fluvial, slope deposits	Till, Mid Pleistocene
Northampton		80.77	26.5 (33%)	8	Glacigenic, fluvial	
Greater London		1594.69	790.04 (50%)	30	Glacigenic, fluvial, coastal, residual deposits, slope deposits	Large areas of bedrock at surface, dominant Quaternary unit is river terrace deposits

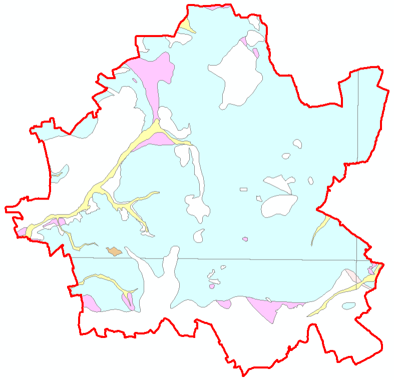
Newark on Trent*		36.21	28.7 (79%)	6	Glacigenic, fluvial, slope deposits	Pre-Ipswichian terrace deposits
Barrow-in-Furness*		132.07	122.84 (93%)	10	Glacigenic, fluvial, coastal, aeolian	Tidal flat deposits

Blackpool*		43.15	40.39 (94%)	9	Glacigenic, fluvial, coastal, aeolian	Till, Devensian
Crawley District*		44.97	9.77 (22%)	5	Fluvial, slope deposits	Mainly bedrock at surface, dominant Quaternary unit is river terrace deposits

Darlington*		197.47	192.1 (97%)	16	Glacigenic, fluvial, slope deposits	Till, Devensian
Middlesbrough*		54.55	54.44 (99.8%)	8	Glacigenic, fluvial, coastal	Till, Devensian
Norwich District*		39.16	28.33 (72%)	7	Glacigenic, fluvial	Glacial sand & gravel

City of Peterborough*		343.43	212.82 (62%)	17	Glacigenic, fluvial, coastal, slope deposits, peat	Tidal flat deposits
Preston District*		142.94	140.54 (98%)	15	Glacigenic, fluvial, coastal, slope deposits	Till, Devensian
Swindon*		230.09	33.1 (14%)	9	Fluvial, residual deposits, slope deposits	Mainly bedrock at surface, alluvium is the dominant Quaternary unit

Torbay*		119.45	4.29 (4%)	6	Fluvial, coastal, slope deposits	Mainly bedrock at surface. Dominant Quaternary unit is marine and coastal zone deposits (undifferentiated)
Warrington*		182.38	171.69 (94%)	11	Glacigenic, fluvial, coastal, aeolian	Till, Devensian

City of Wolverhampton*		69.43	48.39 (70%)	5	Glacigenic, fluvial	Till, Devensian

*Cohort 1 town

Appendix 3 Survey Date of mapsheets

Towns & cities and corresponding 1:50 000 scale map sheet publication dates/survey dates. Where two publication dates are given, (B) indicates bedrock and (S) indicates superficial

Town/city	50K map sheet	Publication date	Survey date
Coventry District	Warwick (184)	1984	1978
	Coventry (169)	1994	1992
Liverpool District	Wigan (84)	2013	1932
	Formby (83)	1942	1937
	Runcorn (97)	1977	1938
	Liverpool (96)	2006	2000
City of Bristol	Bristol (264)	2004	1953
City of Leicester	Leicester (156)	2007	2003
City of Nottingham	Derby (125)	2014	1966
	Nottingham (126)	1996	1993
	Loughborough (141)	2000	1996
	Melton Mowbray (142)	2002	1999
Glasgow City	Glasgow (30)	1993 (B) 1994 (S)	1994
	Airdrie (31)	1992 (B) 2002 (B&S)	1992
	Kilmarnock (22)	2002	2002
Southend-on-Sea	Southend & Foulness (258/259)	1976	1972
Swindon	Swindon (252)	1974	1962
	Marlborough (266)	2016	2016
	Abingdon (253)	1971	1969
	Newbury (267)	2006	2003
Cardiff	Cardiff (263)	1988	1980
Milton Keynes	Towcester (202)	1969	1964
	Bedford (203)	2010	2004
	Buckingham (219)	2002	2000
	Leighton Buzzard (220)	1992	1990
Aberdeen City	Inverurie (76E)	1992	2002
	Aberdeen (177)	2004	2004
	Stonehaven (67)	1999	1999
Birmingham District	Lichfield (154)	2015	1913
	Birmingham (168)	1996	1992
	Redditch (183)	1989	1982

Cambridge District	Cambridge (188)	1981	1953
	Saffron Walden (205)	2002	1882
Oxford District	Witney (236)	1982	1975
	Thame (237)	1994	1990
Felixtowe	Woodbridge & Felixtowe (208/225)	2001	1999
	Colchester & Brightlingsea (224/242)	2010	2008
Ipswich District	Ipswich (207)	2006	2004
Greater Manchester	Preston (75)	2012	2007
	Rochdale (76)	2008	2003
	Huddersfield (77)	2003	2003
	Wigan (84)	2013	1932
	Manchester (85)	2011	2005
	Glossop (86)	2012	2012
	Stockport (98)	1962	1951
	Chapel en le Frith (99)	1962	1961
Sheffield city	Sheffield (100)	2011	2005
	Barnsley (87)	2008	2008
Greater London	Beaconsfield (255)	2005	In progress
	North London (256)	2006	1922
	Romford (257)	1996	1994
	Windsor (269)	1999	1999
	South London (270)	1998	1995
	Dartford (271)	1998	1996
	Reigate (286)	1967	1930
	Sevenoaks (287)	1971	1936
City of Derby	Derby (125)	2014	1966
	Loughborough (141)	2000	1996
Doncaster District	Wakefield (78)	1998	1995
	Goole (79)	1971	1968
	Barnsley (87)	2008	2008
	East Retford (101)	1967	1961
Dundee City	Cupar (48E)	1982 (B) 1983 (S)	1982
	Arbroath (49)	1981 (B) 1980 (S)	1981
City of Edinburgh	Livingston (32W)	2006 (B) 2007 (S)	2007
	Edinburgh (32E)	2003 (B) 2006 (S)	2006
Leeds District	Bradford (69)	2000	1996
	Leeds (79)	2003	2001

	Huddersfield (77)	2003	2003
	Wakefield (78)	1998	1995
Newcastle upon Tyne District	Morpeth (14)	2001	1996
	Tynemouth (15)	1968	1932
	Newcastle upon Tyne (20)	1992	1983
	Sunderland (21)	1978	1975
Newport	Newport (249)	1969	1961
	Chepstow (250)	1981	1939
	Cardiff (263)	1988	1980
	Bristol (Bristol Special Sheet)	2004	1953
Northampton	Northampton (185)	1980	1950
	Towcester (202)	1969	1964
City of Portsmouth	Fareham (316)	1998	1995
	Portsmouth (331)	1994	1984
City of Southampton	Southampton (315)	1987	1980
City of Stoke-on-Trent	Stoke-on-Trent (123)	1994	1992