UK Quaternary: Mapping and modelling the Quaternary - meeting our stakeholder needs

National & International Geoscience Programme

Open Report OR/24/011

BRITISH GEOLOGICAL SURVEY

NATIONAL & INTERNATIONAL GEOSCIENCE PROGRAMME

OPEN REPORT OR/24/011

UK Quaternary: Mapping and modelling the Quaternary - meeting our stakeholder needs

J R Lee, A Finlayson, T Kearsey, R Palamakumbura, S Roberson, K Whitbread

Keywords

Report; Quaternary, mapping, modelling, data matrix, Quaternary Domains, Architectural Elements Analysis.

Bibliographical reference

LEE, J.R., FINLAYSON, A., KEARSEY, T., PALAMAKUMBURA, R., ROBERSON, S., WHITBREAD, K. 2024. UK Quaternary: Mapping and modelling the Quaternary - meeting our stakeholder needs. *British Geological Survey Open Report*, OR/24/011. 36pp.

Keyworth, Nottingham British Geological Survey 2024

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of UK Research and Innovation.

British Geological Survey offices

Nicker Hill, Keyworth,
Nottingham NG12 5GG

Tel 0115 936 3100

BGS Central Enquiries Desk

Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales

Tel 0115 936 3241
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South,
Edinburgh EH14 4AP

Tel 0131 667 1000
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road,
London SW7 5BD

Tel 020 7589 4090
Tel 020 7942 5344/45
email bgslondon@bgs.ac.uk

Cardiff University, Main Building, Park Place,
Cardiff CF10 3AT

Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford,
Wallingford OX10 8BB

Tel 01491 838800

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw,
Belfast, BT4 3SB

Tel 01232 666595
www.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House,
North Star Avenue, Swindon SN2 1EU

Tel 01793 411500   Fax 01793 411501
www.nerc.ac.uk

UK Research and Innovation, Polaris House,
Swindon SN2 1FL

Tel   01793 444000
www.ukri.org

Website www.bgs.ac.uk
Shop online at   www.geologyshop.com

Acknowledgements

The authors of this report would like to thank and acknowledge the range of colleagues that we have worked with and have enjoyed discussions on various aspects of the Quaternary geology and geomorphology of the UK. These have greatly helped to shape the vision expressed within this report. These include but are not limited to: Clive Auton, Stephen Booth, Tom Bradwell, Helen Burke, Ian Candy, Tony Cooper, Bethan Davies, Dave Evans, Jeremy Everest, Paul Fish, Jonathan Ford, Richard Haslam, Leanne Hughes, Maarten Krabendaam, Russell Lawley, Steve Mathers, Andrew McMillan, Brian Moorlock, Tony Morigi, Jon Merritt, Emrys Phillips, Simon Price, Jim Rose, Dave Schofield, Sophie Taylor, Steve Thorpe and Chris Williams.

Contents

List of Figures and Tables

FIGURES

TABLES

Executive Summary

- This report provides an assessment of the strategic significance of Quaternary geology relative to the British Geological Survey (BGS) and its range of UK stakeholders. The report examines the type of information, data and knowledge that is required by our stakeholders and proposes a vision for how BGS will the tackle the Quaternary to deliver this.
- The Quaternary – the last 2.588 Ma of geological time – is one of the most critical parts of the UK geological record. The Quaternary coincides with the geology that occurs in much of the shallow sub-surface. It reflects the part of the geological record most frequently interacted with and utilised by humans, but also the part of the geological record most impacted (buried, eroded and deformed) by the wide range of geological processes that operated during the Quaternary.
- The geological record of the Quaternary is marked by a distinctive variability and heterogeneity that poses significant challenges and risks for BGS stakeholders. Improving our data, knowledge and understanding of this critical part of the geological record is important to help our stakeholders understand and mitigate against geological risks and to inform better planning and decision making.
- BGS has a proven track record of characterising the Quaternary, but our approaches need to evolve to meet the demands provided by: (1) new geological knowledge and understanding; (2) the improved access to increasingly better-quality digital data; (3) the availability of new analytical techniques that enable us to characterise the geology and uncertainty more effectively and quantitatively; and (4) our stakeholder need for quality information, data and guidance at multiple spatial scales.
- In this report we make several strategic recommendations for how our approach to the Quaternary can evolve and how this can be communicated to stakeholders most effectively. We consider that this should occur through the modernisation of the Quaternary Domains dataset; the development of new approaches to classifying and characterising the Quaternary; and the requirement for a spatial dataset or data matrix for storing and managing corporate data and information.

1 Introduction

Deposits, structures and landforms of Quaternary age (the past 2.588 Ma of geological time) comprise a major component of the UK geological record and are synonymous with what we term 'superficial geology'. Quaternary processes have affected the shallow sub-surface succession across all of the UK, both onshore and offshore, by either deforming the rock-mass, eroding it or concealing it beneath a veneer of sediment or 'superficial geology'. Within this broader context, the importance and relevance of the Quaternary to a wide range of UK stakeholder sectors has been long recognised because the shallow sub-surface is the part of the geological record that humans most commonly interact with (Walton and Lee, 2001; Booth *et al*., 2015). The Quaternary commonly induces heterogeneity within the shallow sub-surface, which is unpredictable in properties and extent, posing significant risks to how a wide range of stakeholders can utilise and interact with it (McMillan *et al*., 2000; Dochartaigh *et al*., 2017; Giles *et al*., 2017; Martin *et al*., 2017; Moore *et al*., 2022).

BGS has a strong historical legacy of mapping Quaternary geology and geomorphology through the production of 1:50,000 superficial geology maps (Walton and Lee, 2001; McMillan, 2002). More recently, this has evolved to include the development of 3D geological 'lithoframe' models that incorporate elements of the Quaternary succession. Over the past 10-15 years there has also been a paradigm shift in how geologists more broadly study the Quaternary. This includes both an improved understanding of the processes and systems that have operated within the landscape and shallow sub-surface, plus the greater ability of the geologist to quantify the properties of Quaternary deposits through increased accessibility and quality of digital data (e.g. aerial photographs, digital elevation models etc) and modern analytical techniques (e.g. 3D geological modelling, numerical modelling, terrane analysis, machine learning). At the same time, there has been a growing awareness of the complexity and significance of Quaternary deposits with respect to a range of socio-economic activities (e.g. resources, assets and risks). It is now widely acknowledged the Quaternary forms the dominant component of the so-called 'zone of human interaction' or part of the geological record that humans live-on (or within) and interact with the most for socio-economic gain.

The purpose of this report is to assess the current and future stakeholder needs and requirements for Quaternary-related geoscientific information, and review how current Quaternary approaches utilised by BGS fulfil that information need. We therefore review stakeholder requirements for Quaternary data, information and knowledge; BGS current approaches to the Quaternary relative to current scientific understanding; and finally, propose a series of strategic recommendations that help modernise our workflow through a three-tiered approach to capturing and storing data, characterising the geology for mapping and modelling, and enabling effective communication with stakeholders. This report is therefore a review of BGS's current position but also a statement of intent with respect to future Quaternary needs and how as an organisation we can fulfil that need.

This report and the discussions that underpin it, have been led by the UK Quaternary project, which forms a research theme under the National Geoscience (NG) programme at the British Geological Survey (BGS). The general purpose of the NG programme is to enhance data, knowledge and skills capability linked to the understanding of the geology of the UK, both through its own national good research but also through interacting with our stakeholders. The UK Quaternary project builds on a range of collaborations across NG, including the National Geological Model (now discontinued), but also Quaternary-themed research and product development undertaken within other BGS science (e.g. Environmental Change, Adaption and Resilience programme (EACR) and Multihazards and Risk (MHR)) and information (e.g. Informatics) areas.

2 BGS's Quaternary Stakeholders

2.1 WHO ARE OUR PRIMARY EXTERNAL STAKEHOLDERS?

In the UK, there are a broad and diverse range of stakeholders that require understanding of the geology of the shallow sub-surface and particularly the Quaternary. These can be grouped into five user groups: Local Government, Councils and Authorities; Asset Managers; Resource Managers and Construction; Academic and Research.

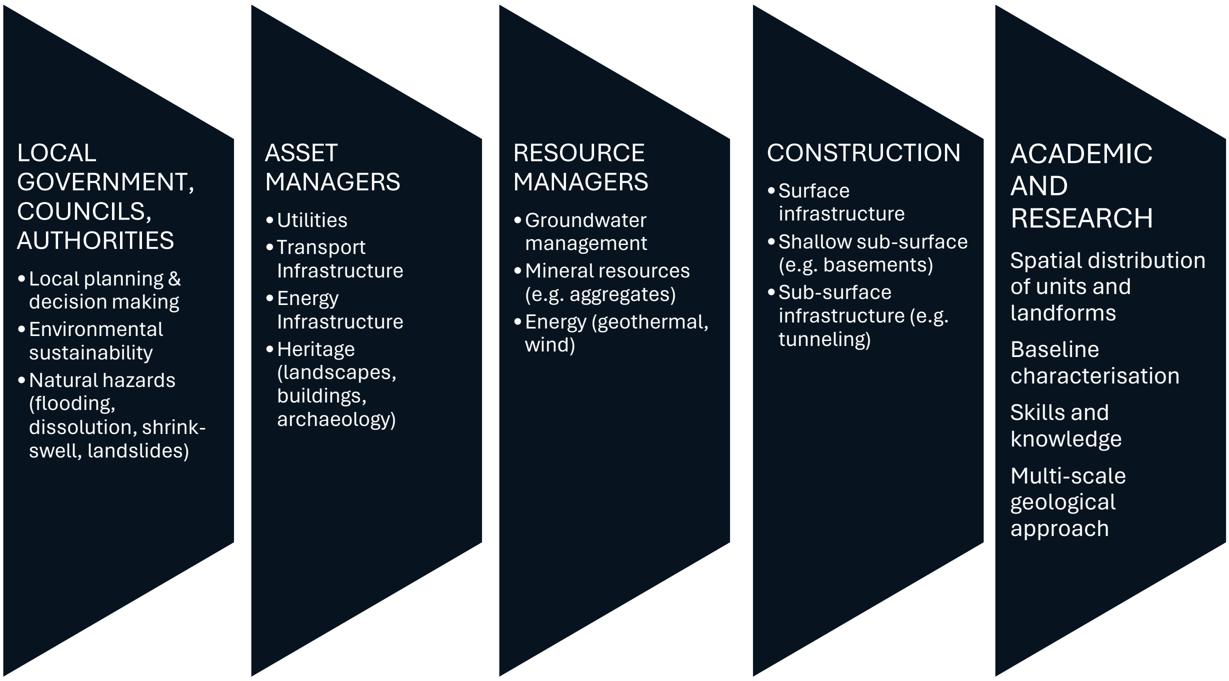


Figure 1. Diagram showing the broad diversity of 'Quaternary' stakeholders and their related applied and research interests.

2.1.1 Local Governments, Councils and Authorities

Local Government, Councils and Authorities encompass a range of public sector bodies and administrative powers that oversee the running of the devolved administrations within the UK. Their primary interest in the geology of the shallow sub-surface and Quaternary is to help facilitate regional / city-scale planning and decision making, environmental protection and sustainability and the management of natural hazards.

2.1.2 Asset Management

Asset Management includes stakeholders that manage sub-surface utility infrastructure including underground pipes (e.g. gas, water mains, drains and sewers), communication cables (e.g. electrical, fibre optic), transport infrastructure (e.g. roads, overground and underground rail) and heritage assets (e.g. landscapes, buildings, archaeology). These stakeholders have a particular interest in understanding ground stability and motion (as a function of ground conditions and neotectonics) because this can cause pipes and cables to fracture and can also lead to increased development of potholes, sink holes and general subsidence issues beneath roads and pavements (Power *et al*., 2012). Ground conditions are also highly relevant to rail infrastructure with 32,000 km of rail track in the UK and over 200,000 related earthwork assets such as embankments and cuttings (Power *et al*., 2016). Over the 20 years to 2019, the volume of rail journeys in the UK has increased by 97% with marked increases in passenger, construction and domestic intermodal freight rail traffic (Dept.for.Transport, 2019). This increase in rail traffic causes greater loads (vertical loading and lateral shear waves) to be applied to the track, trackbed and embankments. Whilst Network Rail has progressively worked to upgrade track and track beds, many embankments were built during the Victorian era and may not be suitable for modern rail traffic demands (Spink, 2020). The London Underground, built between 1862-1999, has an overall network length of 402 km and includes 4 surface-to-subsurface tube lines (Circle, District, Metropolitan, Hammersmith and City) and 7 deep lines (Bakerloo, Central, Jubilee, Northern, Piccadily, Victoria, Waterloo and City). A total of 23 underground stations are at significant risk to flooding due to extreme rainfall events or burst water mains (Russell, 2019). Rising groundwater levels beneath London, due to historical over-abstraction, could also result in flooding of underground stations and also cause changes in the geotechnical properties beneath foundations causing potential settlement (subsidence) beneath escalators.

2.1.3 Resources

The UK has a high and growing demand for a range of **resources** including water, aggregate and energy.

In 2018, the average daily **water** demand for England and Wales was 14 billion litres equating to 143 litres per capita per day (NAU, 2020). The proportion of water lost to leakage through the distribution network was 20% (3 billion litres) per day and it is expected that by 2050, an additional supply of 4 billion litres per day will be required to meet population growth and counter climate change (NAU, 2020). In London, the demand for water is expected to exceed supply by 2040 (TW, 2014) and similar scenarios are evident across much of central and southern Britain. Key water-related stakeholders include: (1) Water Companies (e.g. Severn Trent, Yorkshire Water, Thames Water), who are responsible for providing water and sewerage services to domestic and non-domestic users; (2) Ofwat, the regulator who oversee the performance of water companies; (3) regulators such as the Environment Agency, Scottish Environment Protection Agency and Natural Resources Wales who manage and protect water resources; (4) Local Authorities, who are responsible for implementing sustainable drainage schemes. An understanding of the Quaternary and shallow sub-surface is important for protecting and managing groundwater resources especially where they are wholly or partly concealed by superficial deposits.

Demand for **mineral** resources including sand and gravel aggregate (and crushed rock) are expected to increase markedly with projections demonstrating that 267 million tonnes of aggregate per annum will be needed by 2030 to meet future construction demands (MPA, 2016). The requirement for these aggregates is to support increased housing demand and the implementation of several large national infrastructure projects. The key stakeholders for aggregate resources are major construction companies, aggregate suppliers, The Crown Estate (who manage offshore aggregates) and local authorities.

The demand for **green energy** will also involve stakeholders who have interests in understanding Quaternary geology. Much of this demand is focussed on offshore renewables (i.e. windfarms) where the UK government has set a target of increasing offshore wind power capacity by 25% from 30GW to 40GW by 2030. Understanding the Quaternary is fundamental not only for the design and installation of wind turbine foundations (i.e. monopiles, gravity, jackets) but also for cable routes that transfer the energy back onshore and into the National Grid. Lithological and structural variability, especially in formerly glaciated areas, pose significant geological risks to developers. Ground-sourced heat will also be an area of growth as the UK seeks to reduce its carbon footprint and transition to low carbon forms of energy.

2.1.4 Construction

Construction is one of the major stakeholder sectors across the UK with numerous large-scale projects either operational or planned to upgrade existing transport and utility networks. Major national initiatives include: (1) HS2 which is already under construction between London and Birmingham; and (2) Sizewell C (Suffolk) nuclear power station to compliment Hinkley Point C (Somerset) which is presently being built. Other large-scale construction projects include Crossrail 2, Cambridge to Huntingdon A14 Improvement Scheme, Leeds Flood Alleviation Scheme, Heathrow third runway, Silvertown Road Tunnel (London) and the Thames Tideway Tunnel. The demand for housing is also predicted to grow, driven both by increases in lower-occupancy housing residency and UK population growth which is expected to surpass 71 million by 2045 (ONS, 2022). The main stakeholder with ‘Quaternary’ interests are therefore likely to be:

(1) civil engineers requiring knowledge of ground conditions; (2) resource supply and specifically aggregates; (3) local government from a planning capacity.

2.1.5 Academic and Research

Academic and Research is a major Quaternary stakeholder sector for BGS and largely (but not exclusively) relates to the university sector. Much of the requirement for Quaternary-related data, knowledge and information from this stakeholder sector relates to our historical data (e.g. geological maps, boreholes, specimen collections) and particularly the tacit knowledge and expertise (e.g. process-systems understanding, multi-scale knowledge and skills) of Quaternary geologists at BGS. This has led to the development of many long-standing collaborative relationships between BGS, other geological surveys and leading universities (UK and overseas) that have a strong Quaternary focus. The tacit knowledge and expertise of Quaternary experts at BGS is also highly sought-after by the other four major stakeholder sectors, with expertise widely deployed on a range of Commissioned Research projects, providing expert guidance to government regulators and review panels.

2.2 STAKEHOLDER, DATA AND INFORMATION NEEDS

Over the past 10 years there has been notable shift in the type of Quaternary (and other geological) information, data and knowledge that our stakeholders require. This understanding is based on stakeholder communication, both informally through networking events and contacts, but also more formally through a range of Commissioned Research projects that have been undertaken by BGS Quaternary geologists.

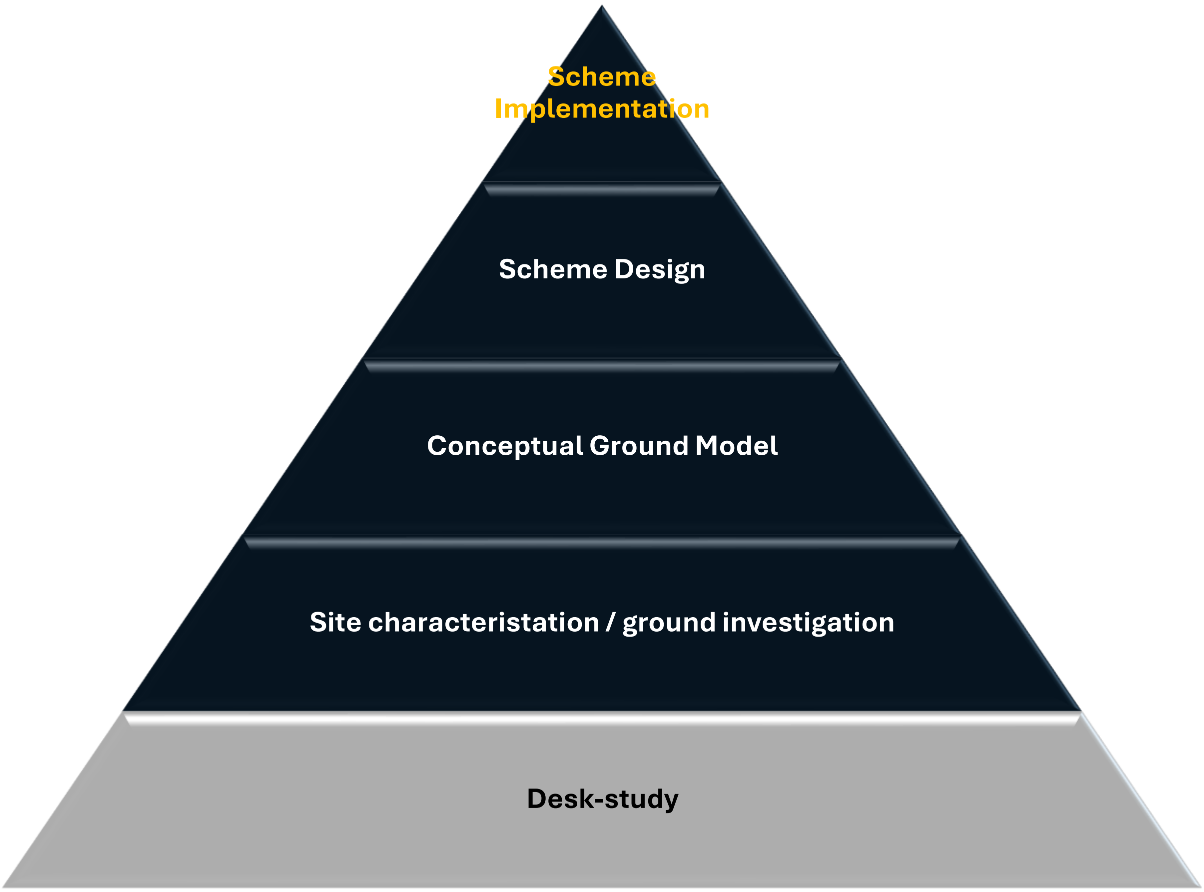


Figure 2. The tiered 'conceptual ground model' to the design and implementation of a ground scheme (McDowell *et al*., 2002; Martin *et al*., 2017). Note that the conventional BGS data (e.g. 1:50,000 data and information) typically form part of the initial desk study.

Many users acquire basic geological information from the traditional 1:50,000 geological map sheet (either digital or hardcopy). This is typically supplemented by reference to published Memoirs, Sheet Explanations and Sheet Descriptions (where available) and the BGS Lexicon and Rock Classification Scheme which provides a stratigraphic and genetic characterisation of the mapping units. This range of information is readily accessible free-of-charge through the BGS website via online portals (e.g. Onshore and Offshore GeoIndex), downloadable / licensed / licensable data (e.g. BGS Geology 50k), webpages (e.g. Lexicon) and reports. Digital scans of the original 1:50,000 maps, memoirs, Sheet Explanations and Descriptions are also available 'free-to-view' to stakeholders via the BGS website link current March 2024 (although hard copy maps and memoirs need to be purchased).

One key aspect of geological maps is that they only provide information on the surficial geology and do not routinely provide information on the subsurface geology at depth, nor the thickness (and variations) of the superficial geological units. In many respects, this spatial information void has in-part been filled by the development of 3D geological modelling although there is limited spatial coverage at a national scale. BGS for instance, developed during the 2000s a 'Lithoframe' regional-scale 3D geological modelling programme, enabling generalised characterisation of the shallow sub-surface (Kessler and Mathers, 2004). 3D geological modelling approaches have proven to be particularly effective in improving science communication. However, underlying issues persist in relation to the geological integrity of many modelling approaches, how uncertainty is communicated, and the often low-resolution of the models which does limit their applicability for many users (Ringrose *et al.*, 2008; Lelliott *et al.*, 2009).

To many specialist users, the type of geological information generated by regional-scale (i.e. 1:50,000) geological maps and 3D geological models can be used to inform the initial desk-study component of a 'conceptual ground model', which in-turn forms part of an extended workflow for the implementation of 'ground schemes' (Figure 2) (McDowell *et al.*, 2002; Martin *et al.*, 2017). However, Knill (2003) and Sullivan (2010) both highlight that whilst this basic type of geological information is relevant, it often lacks resolution, detail and specific information on features of interest that may be relevant to the applied user. For engineering geologists, this often includes a lack of basic rock and soil descriptions that conform to modern best practices (e.g. BS5930:2015). A common issue therefore is that baseline information that underpins the geological map is 'geological' and does not include thematic data or features that are directly usable to applied users (e.g. hydrogeologists, engineering geologists). This issue may in-part reflect a translation issue, with geologists and applied users sometimes employing different nomenclature, or using the same terms differently (e.g. geologist versus engineering geologist definition of 'clay'). However, it also highlights the fundamental issue that parameters used to underpin the stratigraphy for the purpose of constructing a geological map and model are not typically recorded as part of standard geotechnical logging procedures and this needs to be considered for future data capture and 'data model' development.

This demonstrates that applied users have very specific information and scale needs, that these needs vary between applied user sector, and that standard geological information is not always translatable into a form that is directly relevant to the applied user. For example, within city scale planning and zoning applications, 1:50,000 scale geological models are critical to inform effective planning and decision making for managing sub-surface space and resources (Mielby *et al.*, 2016; Mielby *et al.*, 2017). By contrast, for site investigation scale activities, traditional 1:50,000 scale maps and derived lithoframe models are too coarse. This is well-illustrated by stakeholders working on the HS2 and Crossrail projects in London who have only been able to use surfaces from the 'London and Thames Valley 3D Geological Model' to help QA parts of their ground models rather than utilise them as an integral component within them (Anon, pers comm, 2019).

An additional consideration is that the process by which geological observations are converted into a broader stratigraphic classification for both 1:10,000 and 1:50,000 mapping, results in a further generalisation of the primary data. Consequently, any potential applied significance of the geology has to be largely inferred by the user and typically at a broad, non-site scale. In attempting to tackle this issue, BGS have developed a range of derived 'products', including BGS GeoSure, that interpret the baseline geological data for the applied user and communicate it as a series of graded risk maps. However, these are scale specific and do not consistently help tackle the issue the scale needs vary amongst the user community. Geohazard categories within the current BGS GeoSure dataset include: collapsible deposits, compressible ground, landslides, running sand, shrink-swell and soluble rocks. However, these 'value added' datasets are also generalised because of the nature of the original geological data and how it has subsequently been classified.

Many of our stakeholders now seek data, information and knowledge at a range of spatial scales. There is still considerable demand for 1:50,000 geological maps to be updated as part of a nationwide dataset; however, many stakeholders also require higher-resolution site-scale property (lithological and structural) information and data or a broader understanding of geological processes to highlight potential sources of heterogeneity and uncertainty which equate to risk of unforeseen ground conditions.

2.3 SUMMARY

- BGS possesses a wide range of external stakeholders with interests in understanding the Quaternary geology and geomorphology of the UK. These stakeholders can be fitted into four broad categories: (1) local governments, authorities and councils; (2) asset managers; (3) resource managers; (4) construction; and (5) academic and researchers.
- The data, information and knowledge requirements of our stakeholders have progressively evolved over the past 10 years with stakeholders now requiring data, information and knowledge to be provided at a range of spatial scales and increasingly in 3D. Many stakeholders, especially those with their own geological skills and expertise, require 'data-packs' of information rather than traditional 2D map products.
- Whilst there is still demand for 1:50,000 scale information and products (i.e. map data), this data is generally only applicable at the 'desk study' stage of the development of ground model to support a 'ground scheme'. Equally, this scale and type of 'geological' of information does not typically include the specific range of applied descriptors / parameters that are directly useful to users and evidence for these is typically vague and anecdotal.
- One of the key messages from stakeholders was the ability for BGS to be able to communicate potential geological risks either through conceptual and process-based understanding or site-scale observation.

3 The Quaternary: a BGS context

3.1 EVOLUTION OF 'QUATERNARY' AS A GEOLOGICAL DISCIPLINE

Globally, the Quaternary is synonymous with the regular cyclical development of 'Ice Ages' observed in climatic records (Chappell and Shackleton, 1986; Shackleton, 1987). It represents the culmination of a progressive shift in the nature of global climate from the 'greenhouse climates' that dominated the Paleogene (and preceding Cretaceous) to the so-called 'icehouse climates' that define the later parts of the Cenozoic (Figure 3) (Zachos *et al*., 2001). The origin of this climatic shift corresponds to the global configuration of oceans and continents which regulates the efficiency of oceanic and atmospheric circulation of transferring heat and moisture around the planet ('the global conveyer') and cyclical variations in the shape of the Earth's orbit around the sun (called Milankovitch Cycles) which drive changes in seasonality and solar insolation.

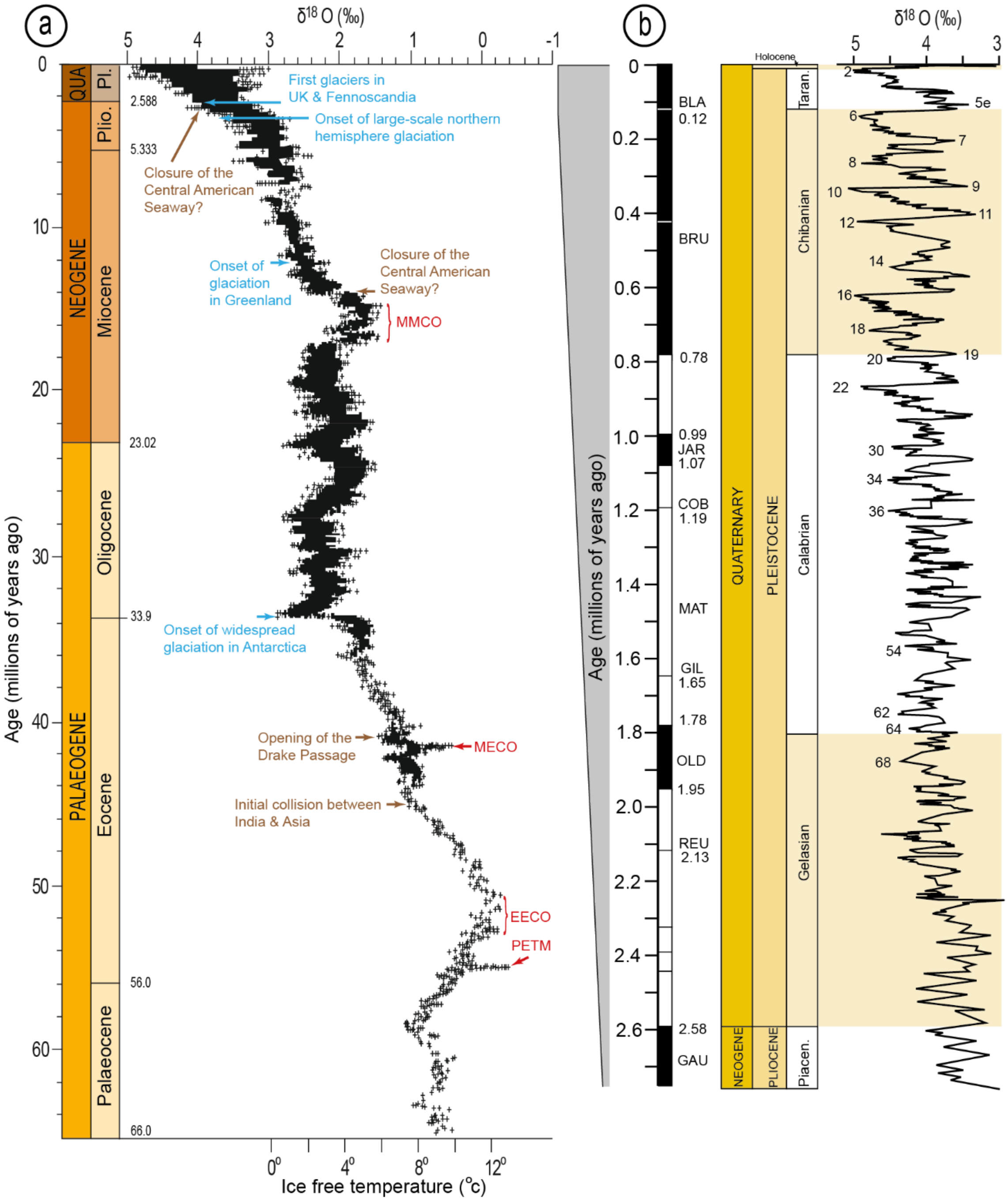


Figure 3. Chronostratigraphic framework for: (a) Cenozoic; and (b) Quaternary. Showing key geological events, benthic oxygen isotope data sourced from Zachos *et al*. (2001) and Lisiecki and Raymo (2005) which is used as a proxy for global ice volume.

In Britain, the significance of the 'Quaternary' in generating the properties of our landscape and shallow sub-surface has long been recognised. This is because Quaternary deposits blanket the bedrock across two-thirds of the onshore landmass and much of our continental shelf. Accordingly, it is the part of our geological record that we most commonly interact with. However, despite being the most commonly used chronostratigraphic subdivision on published geological maps and the branch of Earth Science that possesses the greatest number of active researchers globally, the status of the 'Quaternary' has been hotly debated for over 100 years (Ogg and Pillans, 2008). Opinion has been divided on whether to adopt a 'short chronology' (i.e. 0-1.8 Ma) or 'long chronology' (0-2.6 Ma) for the Quaternary. Formal definition of the Quaternary as a geological System / Period was only formally ratified by the International Union of Geological Sciences (IUGS) as recently as 2009 (Gibbard *et al*., 2010). This led to the base of the Quaternary being established at 2.588 Ma and correlated with the base of the Gelasian Stage and adjusted Pleistocene Epoch (Figure 3).

3.2 BGS'S APPROACH TO THE QUATERNARY

3.2.1 Defining the base of the Quaternary

Prior to the formalisation of the base of the Quaternary by IUGS, BGS employed the 'short chronology' with the base of the Quaternary placed at 1.8 Ma. Whilst this maintained the *status quo* of views held by many scientists during the mid-twentieth century, this interpretation of the Quaternary was largely abandoned by other scientists in the UK and Europe during the early 1990s in favour of the now formalised 'long chronology'.

This inconsistency persists within several onshore BGS maps and datasets, especially in regions such as East Anglia where deposits occur that span the questioned time-interval. It has resulted in deposits, such as the Crag Group and its constituent formations, being mis-attributed as bedrock on published geological maps. To illustrate this point and its impact, Lee (2017) undertook a review of the Rockhead Elevation Model (RHEM v5) within the Crag Basin of East Anglia. The RHEM is a top-bedrock surface model generated by the statistical interpolation of rockhead elevations stored with the BGS Borehole Database. The study identified 12 different regional interpretations of rockhead that have propagated notable errors into the modelled rockhead surface beneath East Anglia - most of these interpretations being a legacy of the stratigraphic issues.

Further clarity has been provided through the stratigraphic revision of Quaternary deposits for both onshore (McMillan *et al*., 2011) and offshore (Stoker *et al*., 2011) stratigraphic nomenclature employed by BGS and the formal adoption of the 'long chronology' of the Quaternary. However, several corporate databases have not yet been updated to reflect this revision. For example, the polygon seeds within BGS's current (pre-2024) digital mapping system called BGS-SIGMA (System for Integrated Geoscience Mapping), still classifies the Crag Group as bedrock.

3.2.2 Approaches to mapping, stratigraphy, and classification

At BGS, our current approach for characterising Quaternary units is underpinned by the BGS Lexicon (McMillan *et al*., 2011; Stoker *et al*., 2011; McMillan and Merritt, 2012) together with – for onshore deposits – the Rock Classification Scheme (RCS) for Natural Superficial Deposits (McMillan and Powell, 1999), with each mappable unit attributed with a 'LEX-RCS' code.

The BGS Lexicon, recently updated as part of a major stratigraphic review of the Quaternary, is a database of hierarchical stratigraphic terms, definitions and generalised properties that are used to classify (stratigraphically) and characterise a mapped unit (McMillan *et al*., 2011). The Rock Classification Scheme, by contrast, is a typology of genetic classes of natural superficial deposits and landforms (McMillan and Powell, 1999). Combined into a 'LEX-RCS' code, this attribute provides a basic attribution of a mappable unit that provides a stratigraphic interpretation and general characterisation of its bulk properties. For example, the LEX-RCS code 'TILLMP-DMTN' describes a Middle Pleistocene till (BGS Lexicon) and diamicton (RCS) as its descriptive qualifier.

Whilst the 'LEX-RCS' characterisation provides a relatively accessible scheme for characterising Quaternary deposits, both the BGS Lexicon and RCS provide the user with relatively generalised information based on stratotype descriptions and conceptually weak lithostratigraphic and genetic assumptions. For example, significant questions have been raised about the applicability of lithostratigraphic approaches in the UK Quaternary – especially in formerly glaciated terranes (see later discussion), which in-turn raises questions about the viability of stratotypes for geological characterisation (Rose and Schlüchter, 1989). Since the publication of the Superficial Deposits version of the Rock Classification Scheme (McMillan and Powell, 1999), significant developments have also occurred in process-based Quaternary geology and geomorphology and this scheme also requires a modernisation. Frequently, neither lithological and / or structural heterogeneity is communicated effectively within LEX-RCS codes, nor are the descriptors readily accessible and / or translatable to other users (e.g. engineering geologists, hydrogeologists). This significantly impacts the direct usability and applicability of our geological maps and information.

Approach	Advantages	Disadvantages
Litho-Genetic	• Applicable in terrains with subdued and / or heavily degraded relief. • Readily accessible data for classification (e.g. boreholes, augering, sections etc). • Accessible skills for describing sediments which focuses on bulk properties. • Stratotype locations will form a known standard.	• Generalised approach that often overlooks lithological and structural heterogeneity. • Common lithostratigraphic principals such as 'way-up', the Law of Superposition and lithological uniqueness not readily applicable beyond local scales. • Tendency of workers to not apply the scheme rigorously. • Stratotype may not be representative of the wider distribution of the unit.
Morpho-Genetic	• Applicable in relatively fresh landscapes where the surface expression of the geology is clear. • Links surface morphology to geology. • Can be useful in areas where natural exposures are lacking.	• Of more limited value in less pristine Quaternary landscapes. • Describes the shape of the surface expression of the geology but not the geology itself.

Table 1. Main stratigraphic approaches used historically by BGS for onshore Quaternary.

Mappable geological units characterised by their LEX-RCS codes form the fundamental stratigraphic building blocks of a geological map. The geometrical relationship between these is built using either litho- or morpho-genetic approaches (Table 1). The litho-genetic mapping approach is a hybrid approach that utilises basic lithostratigraphic principals together with a property and / or process-based genetic classification of deposits to underpin stratigraphic sub-division and define the mappable units (Table 1). An example of a litho-genetic LEX-RCS code is LOFT-DMTN, where LOFT is the LEX stratigraphic descriptor and DMTN is the RCS descriptor. The approach is commonly applied to lowland or heavily degraded (i.e. older) Quaternary terrains where landforms may be subtle or more poorly preserved and bulk lithological and sedimentological properties are accessible. By contrast, the morpho-genetic mapping approach utilises a morphostratigraphic classification where stratigraphic attribution and sub-division is underpinned by the cross-cutting relationship between different landforms, landform assemblages and their genetic properties. An example of a morpho-genetic LEX-RCS code is MORD-DMTN, where MORD is the morphological descriptor for 'morainic deposits', and DMTN is the RCS descriptor. This mapping approach is routinely applied to upland and younger Quaternary terranes, where morphological features in the landscape are better preserved (Table 1). A more pseudo-lithostratigraphic approach is often utilised by BGS 'lithoframe' 3D geological models using either lithostratigraphic nomenclature or bulk lithological properties (Figure 4).

Figure 4. The influence of the BGS Lexicon and Rock Classification Scheme (RCS) on downstream products and activities.

With litho-genetic mapping classifications, the principal limitation of the approach is that the characterisation of a unit is based principally upon its form within the landscape and a lithological attribution is often assumption-led based upon the RCS (Figure 5). A litho-genetic approach is underpinned by standard lithostratigraphic principles based upon the assumption that Quaternary sequences can be characterised – much like parts of the sedimentary bedrock record, using lithostratigraphy. Lithostratigraphic approaches are not easily applicable to the onshore Quaternary of the UK. This is due to the generally limited sediment accommodation space within the landscape, the propensity of hillslope and fluvial processes acting to remobilise materials coupled with the influence of glacitectonic processes that erode and deform pre-existing substrate materials. Collectively, these processes limit sediment preservation, restrict lateral facies continuity and in the case of glaciation impart a tectonic imprint to a sequence (e.g. repeated / inverted strata). The value of lithostratigraphy within this context is therefore limited (Rose and Menzies, 2002; Hughes, 2010; Lee, 2018). The value of stratotype locations, whilst commonly utilised in UK Quaternary lithostratigraphic schemes (Mitchell *et al*., 1973; Bowen, 1999; McMillan *et al*., 2011), also has limited practical spatial value due to the notable heterogeneity of Quaternary deposits (Rose, 1989). Morpho-genetic mapping classifications, whilst providing a suitable mechanism for rapid mapping, are over-reliant upon genetic assumptions to characterise unit lithology and properties – a key knowledge criteria for our stakeholders. In many instances, such an approach fails to communicate the lithological and / or structural heterogeneity of the Quaternary deposits accurately. This is especially the case in formerly glaciated terrains where understanding of sediment-landform assemblages and glacial processes has developed significantly over the past 20 years through the evolution of an integrated ‘glacial landsystems’ approach to characterising and interpreting glacial geology (Evans, 2003; Benn and Evans, 2014; Evans and Benn, 2021).

Figure 5. Litho-genetic mapping of glacial lake sediments in the Vale of York using surface morphology and a soil auger to capture shallow cores of sediments. © BGS 2024.

A review and modernisation of the BGS Lexicon, Rock Classification Scheme and mapping approaches is therefore needed for superficial geological mapping (and contained information) to meet stakeholder requirements. Such an approach needs to embrace new data and technologies but critically be driven by process-understanding of the geology / geomorphology to more effectively characterise material properties (lithological and structural) and spatial heterogeneity.

3.2.3 Approaches to 3D geological modelling

3D geological models have over the past twenty years formed an increasingly important component of how BGS geologists communicate geology, due to the increased awareness and requirement from our stakeholders for better geological understanding of the shallow sub-surface (Ford *et al*., 2010). BGS has formerly undertaken 3D geological modelling at regional to national scales, with datasets forming part of a 'National Geological Model' that sought to develop knowledge of UK geology at a range of spatial scales and for different parts of the geosphere.

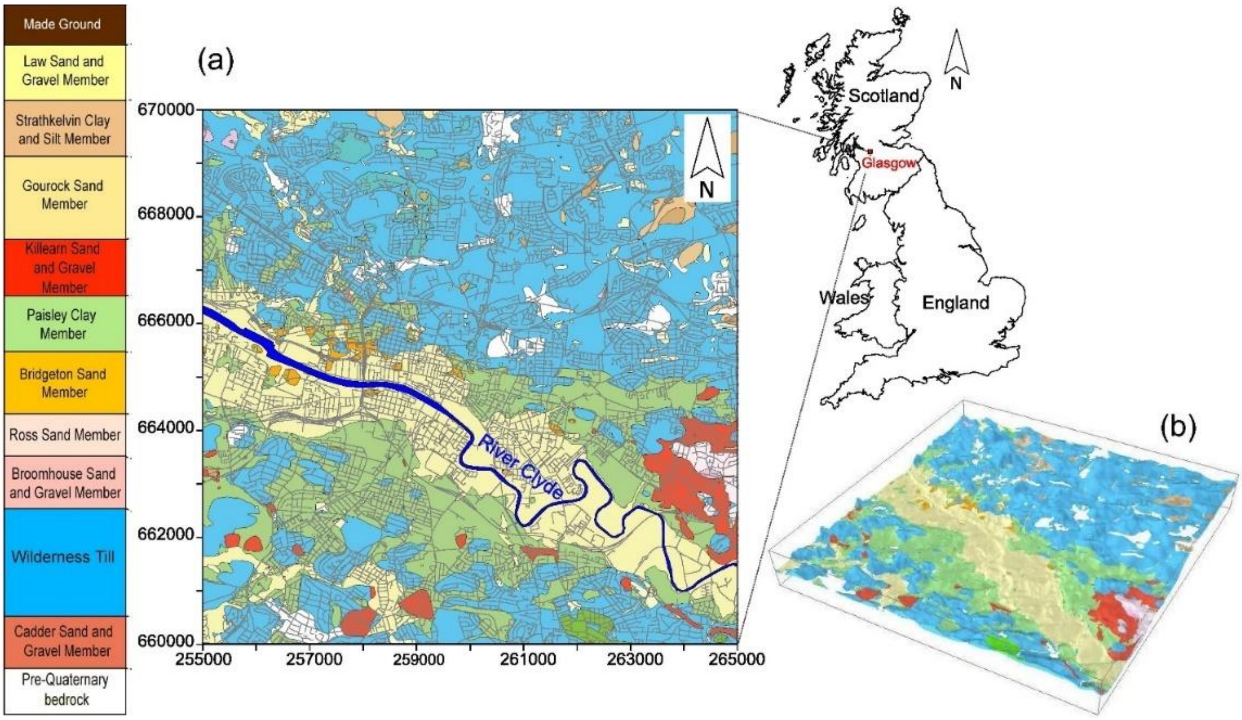


Figure 6. Mapping and GSI3D model outputs for the Glasgow Geological Model (Merritt *et al*., 2012). © NERC 2012.

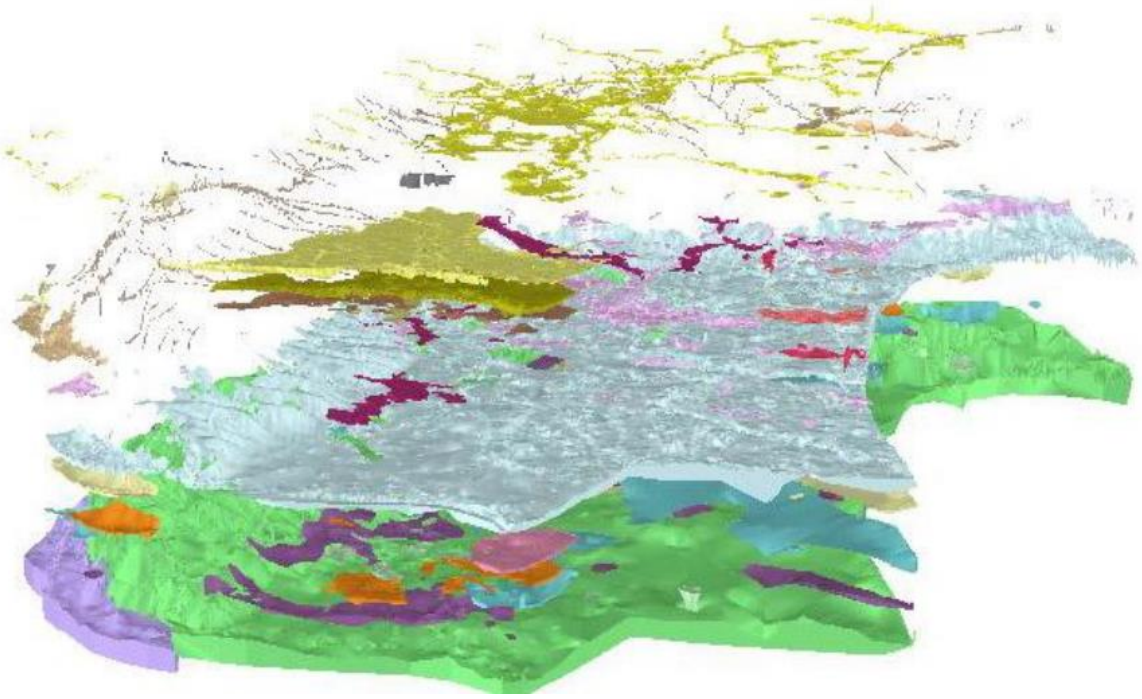


Figure 7. Exploded view of the Quaternary 3D geological model for Kingston upon Hull showing a thick till (blue) sequence covered by a veneer of sand and gravel (pink) and Holocene alluvium (yellow) (Burke *et al*., 2009). © NERC 2009.

Many regional-scale model outputs (**Error! Reference source not found.**) have been developed by BGS to support city-level (e.g. Manchester, Cardiff, Glasgow, London) planning and decision-making (Merritt *et al*., 2012; Mathers *et al*., 2014; Kearsey *et al*., 2017); whereas numerous other bespoke regional-scale 3D geological models have been commissioned by stakeholders to help them manage specific resources (e.g. water) and understand potential variations in ground conditions (Rutter *et al*., 2006; Aldiss *et al*., 2012; Bricker *et al*., 2014).

BGS has traditionally undertaken much of this 3D geological modelling using the GSi3D modelling software (Kessler *et al*., 2009) and more latterly Groundhog modelling software. Use of GSi3D and Groundhog within modelling projects has now ceased, but both modelling platforms produced raster models in similar ways, by utilising existing surface / sub-surface information (i.e. interpreted borehole logs, geological maps, digital elevation model) and a geologist's tacit knowledge to manually construct an interconnected network of cross-sections. The modelling software then performed a statistical interpolation to calculate the sub-surface distribution of the geological units and generate the model outputs (e.g. 3D geological model, gridded surfaces, volume etc; **Error! Reference source not found.**) (Kessler *et al*., 2009).

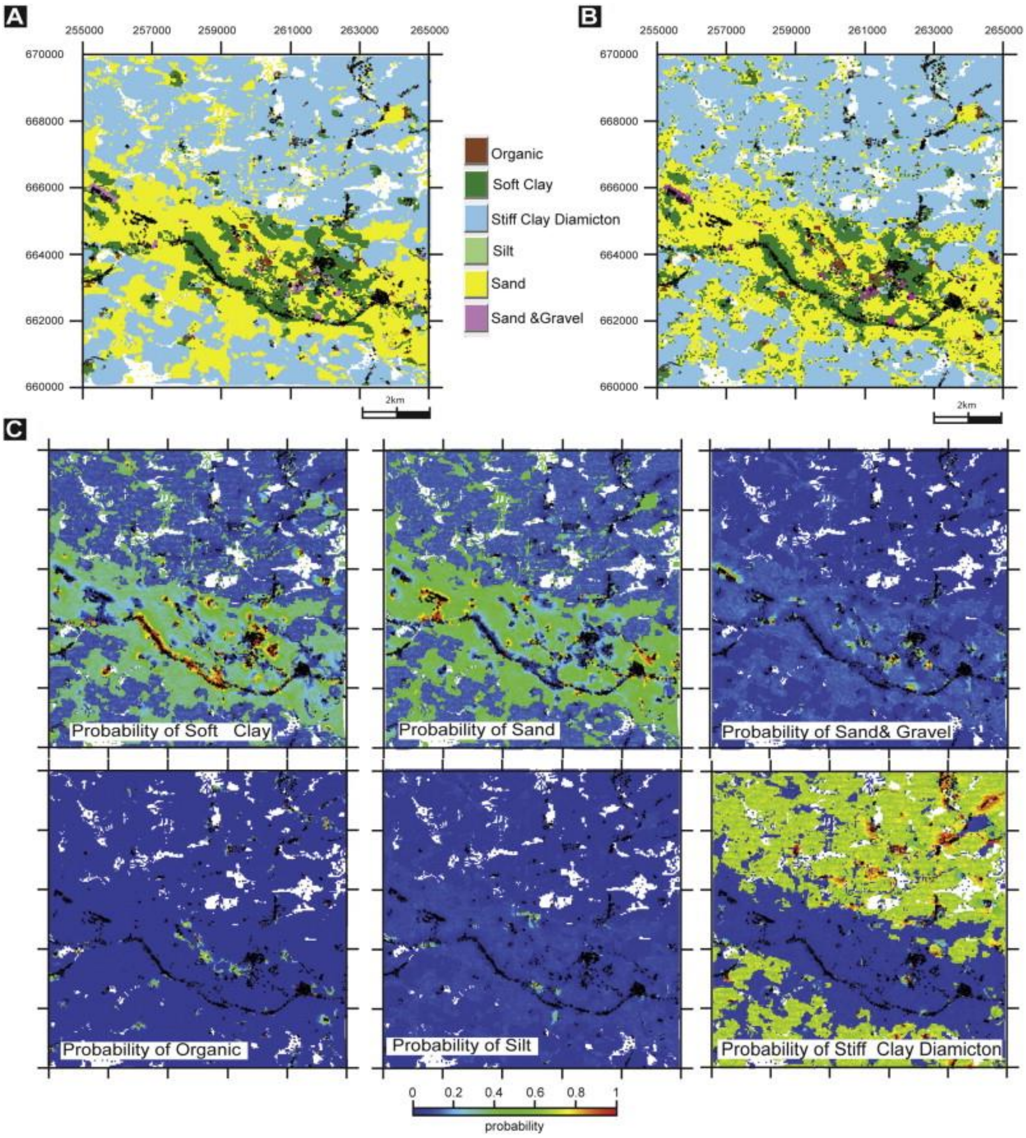


Figure 8. Stochastic geological model outputs from the Glasgow 3D geological model (Kearsey *et al*., 2015). Showing the development of different predictive geological maps based upon Indicator Kriging (A) and Sequential Indicator Simulation (B) stochastic model approaches, and the probability of different lithologies occurring in subcrop (C). British Geological Survey © UKRI 2018.

Whilst the development of these modelling approaches transformed how BGS geologists communicated geological information, these modelling approaches do have limitations. As previously explained, pseudo-lithostratigraphic approaches to geological classification and characterisation have significant practical issues when applied to a Quaternary context.

This is because the approach leads to a generalisation of geological information which does not effectively communicate the inherent lithological (and sometimes structural) complexity of the Quaternary record. It is typically this complexity – and a potential lack of awareness of its existence or impact, that represents a significant risk to stakeholders. In an attempt to more effectively characterise and quantify this geological complexity, BGS geologists also utilise more stochastic voxel-based 3D geological modelling approaches (Figure 8) within the Quaternary (Kearsey *et al*., 2015). This type of modelling approach enables the geologist much greater tacit input into the modelling process by controlling the correlation range parameters used in the stochastic modelling. This should in theory, enable much more geologically plausible extrapolation of the geology between data points enabling probabilistic models to be developed and uncertainty to be more effectively qualified (Figure 8).

3.3 SUMMARY

- Formal recognition of the Quaternary as a 'period' within the global geological time scale was only achieved in 2009 with its base established at 2.588 Ma. Previously, there was a diversion of views with some advocating a 'short chronology' for the Quaternary (0-1.8 Ma) and others endorsing a 'long chronology' (0-2.6 Ma).
- BGS has historically been a proponent of the 'short chronology' for the Quaternary; however, since the 2000s, BGS has formally adopted the 'long chronology'. Several artefacts of this chronological switch persist in some corporate systems, including some superficial deposits that have been classified as bedrock and the misinterpretation of rockhead coded within boreholes in parts of eastern and southeast England.
- The Quaternary geological record within the UK is inherently complex and poses significant challenges to geologists and in-turn applied users. Specific geological challenges include: (1) the restricted availability of landscape accommodation space limits stratigraphic continuity; (2) the presence of active geological and geomorphological processes that erode and redistribute materials at different levels within the landscape; (3) the cyclical activity of climate-driven processes that form replicated sequences (including lithological signatures) and / or landform assemblages; (4) multiple phases of glaciation which are significant agents of landscape change; (5) the dominance of tectonic over sedimentary processes within glacial environments means that common lithostratigraphic rules cannot routinely be applied; and (6) the temporal resolution (days to thousands of years) and preservation of the geology and geomorphology in the Quaternary is very high. Collectively, these challenges constrain how geologists can characterise and classify the geological properties of the shallow sub-surface.
- BGS traditionally employs litho-genetic and morpho-genetic mapping approaches for mapping and characterising the Quaternary, underpinned by corporate dictionaries (i.e. the BGS Lexicon) and typologies (Rock Classification Scheme for Natural Superficial Deposits). A pseudo-lithostratigraphic approach also underpins the majority of the 3D geological modelling that we currently undertake. However, whilst suitable for regional-scale mapping and modelling characterisation, these approaches are very generalised and undermined by practical / conceptual weaknesses. In short, they do not communicate the complexity (lithological and / or structural) of the Quaternary adequately – or sometimes in directly comparable terminology, that meets our stakeholders' needs because it is this geological complexity that creates an applied risk to our users.

4 BGS Quaternary – the future

4.1 INTRODUCTION

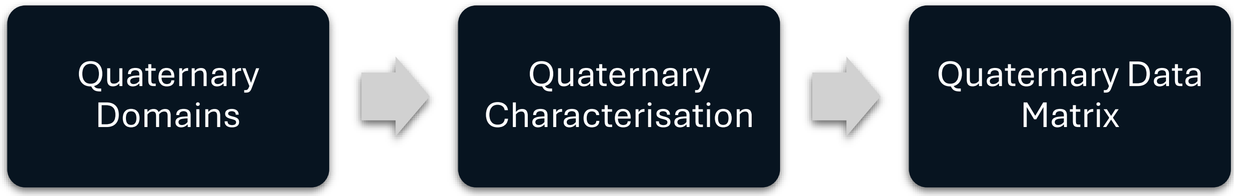


Figure 9. The three-tiered approach to more effectively characterising and communicating the Quaternary.

Within this section of the report we present a future vision for how BGS may continue to actively support stakeholder needs by providing knowledge, information and data on the Quaternary geology of the UK. BGS has a strong tradition of being a science leader within the UK Quaternary. However, the workflows that underpin the geological mapping and especially the 3D lithoframe modelling need to be updated to reflect both our stakeholders evolving needs and developments in scientific and technical understanding / capability. We recommend a three-tiered approach to more effectively communicate and characterise the Quaternary (Figure 9).

4.2 QUATERNARY DOMAINS

Making Quaternary information, data and knowledge more accessible to the BGS stakeholder community is a key objective for the UK Quaternary project. In very general terms, if science isn't communicated effectively then it has no practical value. In response to this objective, UK Quaternary is currently developing an upgrade to Quaternary Domains as its primary communication mechanism.

The concept of Quaternary Domains was developed during the 2000s by BGS as a mechanism for communicating the properties (geological and geomorphological) of the Quaternary onshore landscape in a simplified and accessible way to stakeholders. The Quaternary Domains approach, developed at 1:625,000 scale, produced a 10-fold domain-level classification of the UK (Figure 10) with each domain possessing a semi-quantitative definition based on its geological and geomorphological properties and the geological processes that have shaped it, a series of schematic cross-sections and basic guidance on practical geological issues that may be of relevance (Booth *et al*., 2010; Booth *et al*., 2015). The dataset was released as an Open Report (Booth *et al*., 2010), a peer-reviewed published paper (Booth *et al*., 2015) and a dataset viewable online via the BGS Onshore Geoindex.

Quaternary Domains has proved highly-popular with industry stakeholders, especially hydrogeologists and civil engineers, who typically employ the scheme as part of an initial desk study activity that informs the conceptual ground model of a 'ground scheme' (McMillan *et al*., 2000; McMillan, 2002; Booth *et al*., 2015). However, the accessibility of digital data, modern digital / numerical analytical techniques and advanced web delivery make a modernisation of Quaternary Domains necessary. As part of the UK Quaternary project, Quaternary Domains will be updated to more effectively parameterise the properties of the landscape and shallow sub-surface using a range of numerical geological and geomorphological properties and highlighting uncertainty, heterogeneity and potential geological risks to different stakeholder groups.

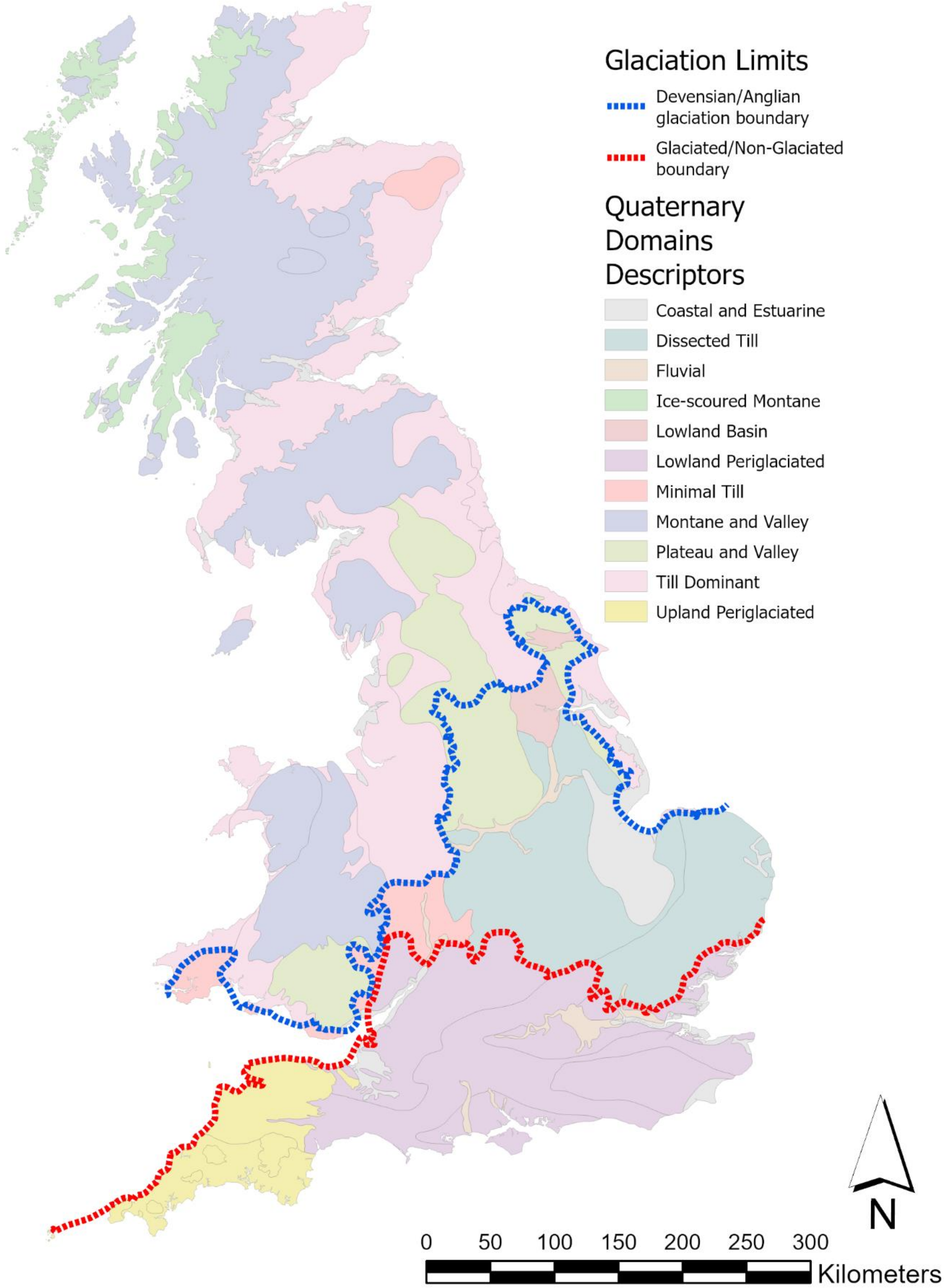


Figure 10. The distribution and classification of Quaternary Domains across the UK based upon a collaborative BGS program of work undertaken during the 2000s. The Quaternary Domains classification sub-divided the Quaternary landscape of the UK into ten domains based on the dominant properties of the landscape and shallow sub-surface.

Approach	Framework defined by:	Stratigraphic application	Advantages	Disadvantages
Lithostratigraphy	Site- to local-scale framework defined by lithological character and stratigraphic relationships	Mainly non-glaciated terrains.	Accessibility of baseline data (e.g. sections, lithological descriptions, boreholes etc). Applicable to both vector and raster modelling approaches.	High data-rich requirement for good quality lithological data (e.g. engineering boreholes, site description etc). Characterisation can often become generalised so heterogeneity is often overlooked. Many core lithostratigraphic principles are not readily applicable to the Quaternary (e.g. lithological similarity = stratigraphic equivalence; way-up, law of superposition) Limited application in glaciated terrains which comprises much of the UK.
Allostratigraphy	Multi-scale bounding (site to national scale) surfaces and discontinuities	All types of Quaternary geology	Can if applied robustly, help to reconstruct the geometry of the sequence. Readily applicable to sections and seismic data; Applicable to a range of different types of Quaternary geology.	Requires effective sub-surface characterisation by boreholes and geophysical data. Approach doesn't by default characterise the properties of the sediments. Development of a consistent hierarchical approach can be difficult due to scale and data availability.
Architectural Elements Analysis	Multi-scale hierarchical approach (site to national scale) of bounding surfaces, lithofacies.	All types of Quaternary geology	A well-rounded approach that utilises components of lithostratigraphy, allostratigraphy and process understanding. Can effectively draw together section observations with borehole data and seismic / geophysical data.	Requires effective sub-surface characterisation by boreholes and geophysical data. Development of a consistent hierarchical approach can be difficult due to scale and data availability. Requires effective facies models and associations developed from modern analogues.
Morphostratigraphy	Morphology and surface textures	Relatively pristine landscapes with good geomorphological preservation.	Widespread application especially in pristine terrains.	More limited application in heavily degraded terrains. Does not provide an effective characterisation of the sub-surface.
Kinetostratigraphy	Multi-scaled hierarchical approach (site to national scale) utilising ice movement indicators and deformation history.	Glaciated terrains	Like allostratigraphy, a powerful tool for building a geometric understanding of the sequence.	Specialist knowledge required. Requires effective sub-surface characterisation by boreholes and geophysical data. Approach doesn't by default characterise the properties of the sediments. Development of a consistent hierarchical approach can be difficult due to scale and data availability
Biostratigraphy	Palaeontological indicators	Organic sediments or units that preserve organic material	Wide range of macro- to micro-scale palaeontological indicators can be employed; ability to characterise an environment and deposition setting.	Specialist knowledge required. Not all fossils are age diagnostic. Expensive laboratory analysis if geochemical data is required.

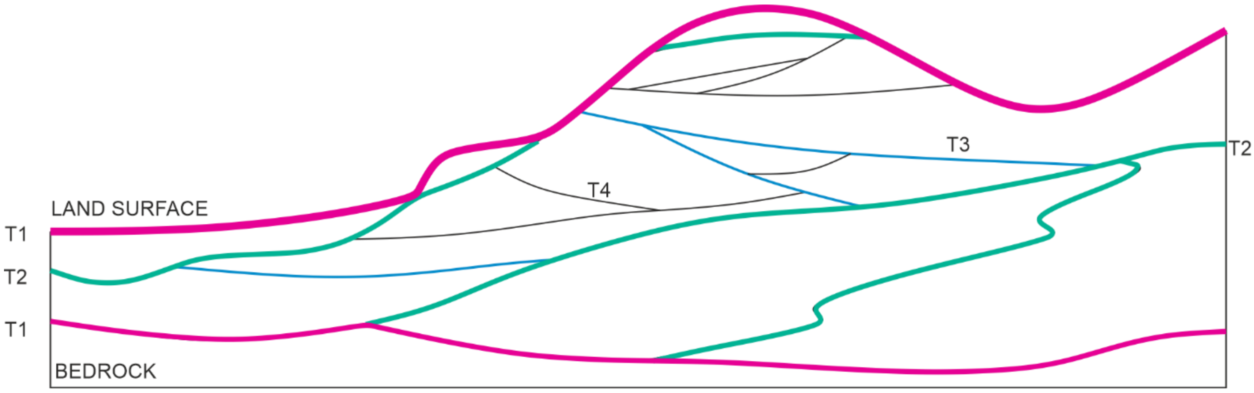
Table 2. Table summarising the main relative stratigraphic approaches employed within the Quaternary, their application and advantages and disadvantages to the approaches.

4.3 QUATERNARY CHARACTERISATION

4.3.1 Quaternary stratigraphy

As BGS moves into a more integrated mapping and modelling workflow for characterising Quaternary geology, so our mechanisms for communicating the Quaternary to meet our stakeholder needs also needs to evolve. ‘Stratigraphy’ within this context refers to the relative arrangement of geological units within a mappable succession. Conventionally, BGS uses Litho- and morpho-genetic mapping and stratigraphic approaches, and these will continue to form the basic approaches for characterising the superficial geology. However, major overhauls of stratigraphic approach, the BGS Lexicon and Superficial Deposits Rock Classification Schemes are required to provide effective and modern information on our maps (and to our stakeholders), standardise our workflows and meet new scientific and modelling challenges.

A range of different stratigraphic techniques are accessible to the geologist for application within Quaternary terrains (Table 2). These various stratigraphic approaches utilise different geological proxies to underpin a stratigraphic classification and individually have their advantages and disadvantages (Table 2). However, none of these stratigraphic techniques can individually characterise the Quaternary in a way that is both geologically robust and is able to communicate the complexity of the Quaternary record. Arguably, the strength of these approaches is collectively as a tool-kit which can be utilised flexibly to meet the scientific, modelling and technical demands of a specific project.



SYMBOLOGY	DEFINITION
	TIER 1: SUPERFICIAL SEQUENCE BOUNDING SURFACES Incorporating rockhead surface and land surface
	TIER 2: BOUNDING SURFACES SEPARATING GROUPS DIFFERENT GENETIC CLASSES Bounding surface separates group-level stratigraphy and different genetic sediment packages
	TIER 3: FORMATION BOUNDING SURFACES Bounding surface separating different formation-level stratigraphy including decollement surfaces
	TIER 4: INTRA-FORMATION BOUNDING SURFACES Bounding surface separating different mappable units within a sequence

Figure 11. A conceptual ‘allostratigraphic’ approach for characterising Quaternary deposits. The approach provides a hierarchical characterisation of bounding surfaces that constrain the superficial deposits (T1) and form intra-sequence boundaries between different sediment-landform packages (T2-T4).

A key recommendation is to change what we capture as the major stratigraphic ‘elements’ of the Quaternary. Currently, these ‘elements’ relate to the geological units themselves and are defined conventionally by pseudo-lithostratigraphic, litho-genetic and morpho-genetic parameters. However, as outlined within the previous report chapter, these approaches have significant practical limitations when applied to the UK Quaternary and this undermines our ability to communicate the complexity of the geology and underlying risks to our stakeholders. A more practical approach, in the first instance, would be to utilise the hierarchical arrangement of the major ‘bounding surfaces’ as the key Quaternary stratigraphic-defining ‘elements’ (Figure 11) –

an approach called 'allostratigraphy' (Räsänen *et al*., 2009) (Table 2). The primary advantage of allostratigraphy is through the utilisation of bounding surfaces to accurately constrain the geometry and relationship between different packages of sediment – including surface morphology. This will enable geologists to understand more effectively how different geological processes have interacted with the landscape and how the sequence has developed event-by-event.

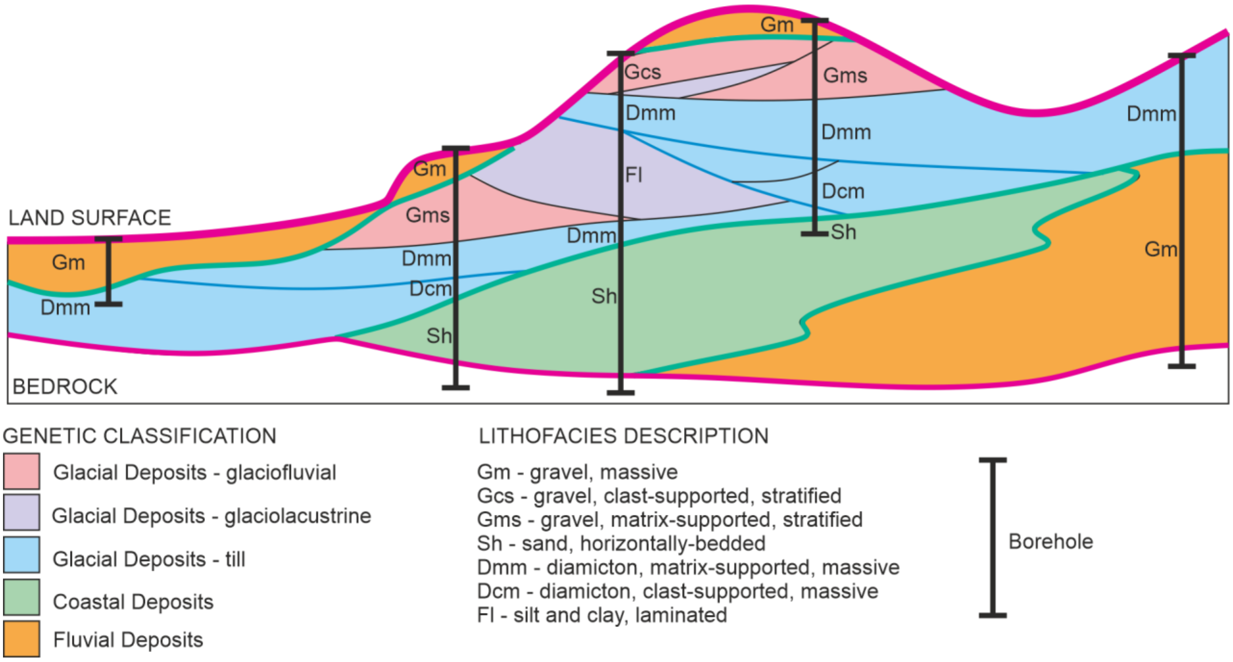


Figure 12. Lithofacies overlay of the allostratigraphic model showing the distribution of sediment types and genetic classes (see also Figure 11). This combined approach utilising both a lithofacies and allostratigraphic approach is called 'Architectural Elements Analysis'.

By evolving this allostratigraphic approach through the attribution of bounding-surface constrained 'lithofacies' and genetic interpretation, a more sophisticated and predictive geological model utilising 'Architectural Elements Analysis' (Miall, 1985) and 'glacial landsystems' (Evans, 2003) can be developed. This hybrid approach focusses on reconstructing the stratigraphic hierarchy of key bounding surfaces within Quaternary sequences and also characterising the lithological and morphological units between these surfaces (Figure 12). A key aspect of this approach is the use of modern and recent geological analogues in constraining and predicting the broader geological framework and properties.

This dual approach would greatly enhance the geological robustness of a 3D geological characterisation and naturally builds upon our current mapping litho-genetic and morpho-genetic mapping approaches. Utilising analogues to constrain the 3D geological characterisation would improve our process-based geological understanding which ultimately will help geologists to effectively constrain / predict the geology in areas (or at scales) with more limited data coverage and assist in developing a far more effective understanding of heterogeneity and uncertainty. Architectural Elements Analysis has been widely applied elsewhere to glaciated and fluvial terranes (Miall, 1985; Boyce and Eyles, 2000; Heinz and Aigner, 2003; Slomka and Eyles, 2013; Slomka and Eyles, 2015; Slomka *et al*., 2015) and would therefore be highly-applicable to UK Quaternary terranes. Evolving our corporate approach to characterising the Quaternary would be necessity require staff training and changes to existing workflows, methods and software and the communication of these changes to stakeholders.

4.3.2 BGS Lexicon and Superficial Deposits Rock Classification Scheme

Both the BGS Lexicon and Superficial Deposits Rock Classification Scheme need to be modernised to enable the lithological and structural heterogeneity of a unit characterisation to be more effectively characterised and communicated to our stakeholders.

4.4 QUATERNARY DATA MATRIX

Earlier sections of this chapter have focussed on how Quaternary data, knowledge and information can be communicated (Section 4.2) and characterised (Section 4.3) more effectively. An additional element for consideration is how Quaternary data, knowledge and information is managed and stored. Currently, the primary storage for this data, knowledge and information is: (1) published 1:10,000 and 1:50,000 geological maps; (2) field slips and BGS-SIGMA ESRI database files (some of which are within the corporate ORACLE database); (3) various implicit and explicit 3D geological models; (4) various reports, memoirs and peer-reviewed literature; (5) coded boreholes with borehole geology; (6) corporate dictionaries (e.g. BGS Lexicon) and typologies (e.g. RCS); and (7) tacit knowledge held by individual geologists. Accessing this information is complex and inefficient, incorporating a range of hardcopy, hard digital and soft digital datasets. The latter includes many of the scanned maps and publications which are typically viewable but where data (e.g. point observations etc) have not been digitally mined and incorporated into hard digital data.

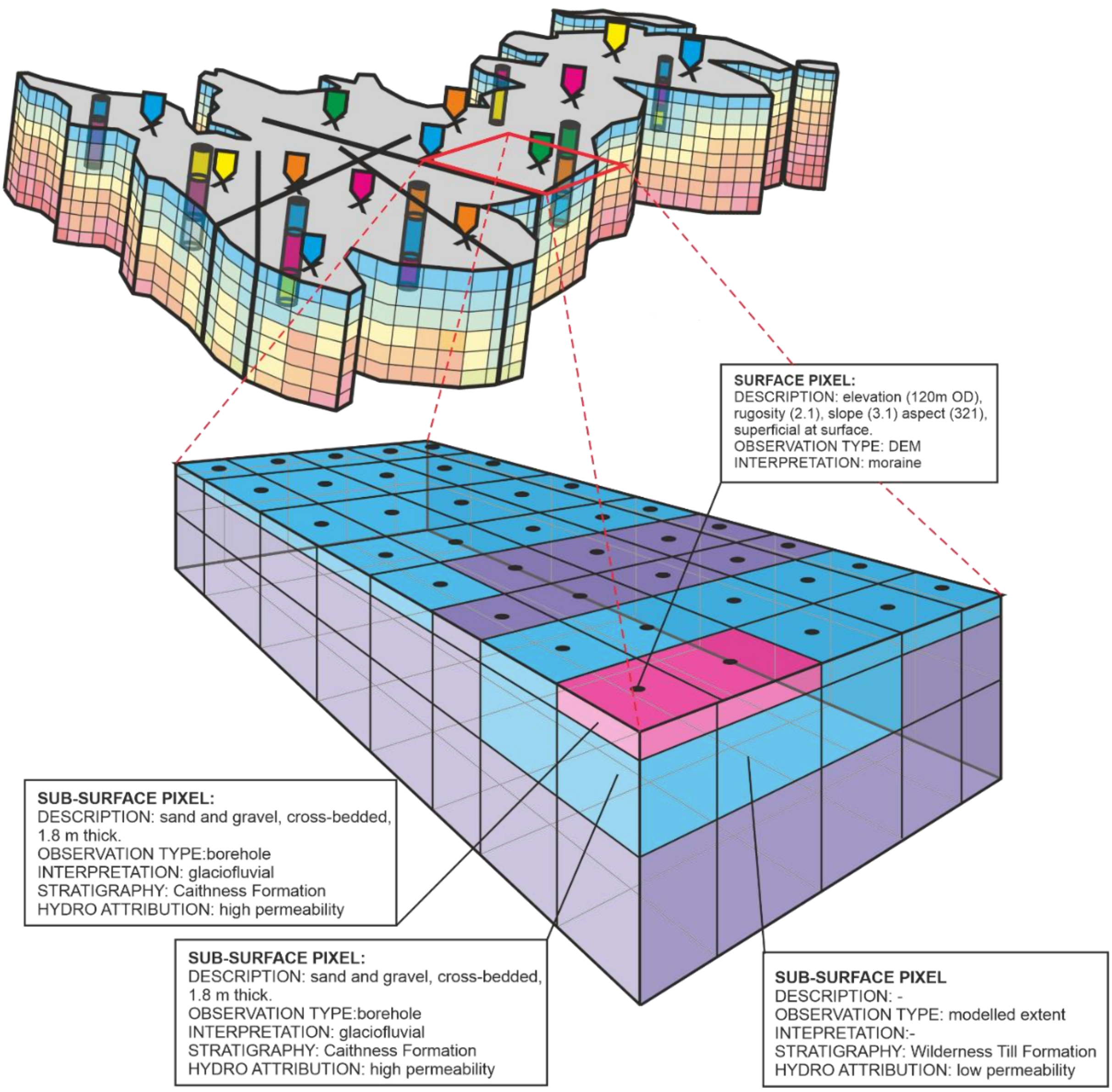


Figure 13. A 3D block diagram showing a conceptualisation of the '3D gridded data matrix'. Each pixel within the gridded matrix can be characterised based on a range of surface and sub-surface parameters. The grid can be populated by direct observation (e.g. field-based observation, remote sensing or ground investigation) point data. Extrapolation between data points could be undertaken using a range of geostatistical and machine learning techniques.

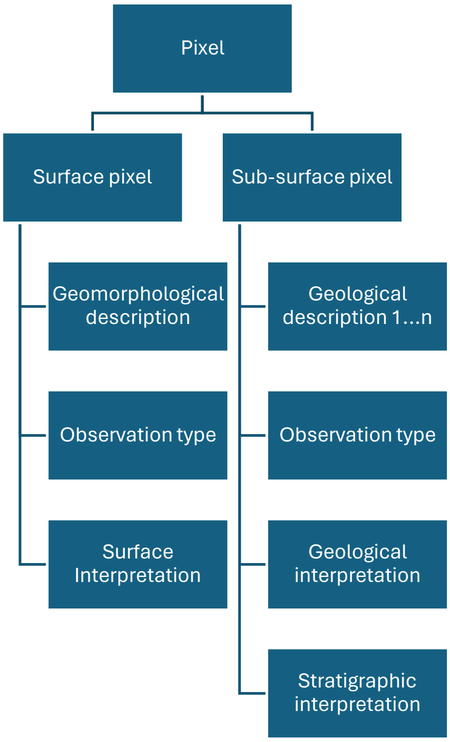


Figure 14. Workflow for 3D gridded matrix attribution.

SURFACE CHARACTERISATION		SUB-SURFACE CHARACTERISATION		SUB-SURFACE APPLIED CHARACTERISATION	
Geomorphological description	Rugosity, aspect, slope, elevation, rock at surface?	Geological description	Lithology, texture, colour, structure, thickness	Geotechnical description	PSA, shear strength
Observation type	Direct, DEM, aerial photos	Observation type	Section, borehole, SI, model-derived	Hydrogeological characterisation	Permeability, porosity
Geomorphological interpretation	RCS attribution	Geological Interpretation	RCS attribution		
		Stratigraphic attribution	BGS Lexicon		

Table 3. Hierarchy of different attributes that could be used to parameterise the grid matrix.

To synchronise and utilise these data sources effectively, in a modern and interoperable way, it is recommended that a range of spatial Quaternary data (e.g. simple point, complex point, line, region) could be collated and stored as part of a '3D data matrix' available through a spatial index (Figure 13). This data matrix would cover both the ground surface and extend downwards through the geological column to the rockhead surface. Each surface and/or subsurface grid within the matrix could then be parameterised relative to a range of descriptive, interpretative and applied attributes (Figure 14). A range of different descriptive, interpretative and applied parameters could be collected and stored as part of the matrix (Table 3).

A key concept of the 3D data matrix' is that it is a live database of geological description and interpretation of the surface geomorphology and shallow sub-surface geology. The database should be fully updatable through the use of spatial datasets such as Digital Elevation Models that can characterise the surface, point-based data such as field observations and site investigation data (e.g. boreholes, trial pit data) for the sub-surface, as well as line and polygon-based data (e.g. faults, map interpretations). The database should be interoperable with machine learning and numerical modelling platforms which could be used to extrapolate the sub-surface characterisation between data points. Several studies have attempted a similar gridded for data management and modelling approach for generating soil property (Hengl *et al.*, 2021) and surface geological maps (Sang *et al.*, 2020; El Fels and El Ghorfi, 2022) as well as characterising the shallow sub-surface (Stafleu *et al.*, 2011; Kearsey *et al.*, 2015).

The aim of the matrix approach would be to provide a flexible dataset that could be easily and quickly deployed to generate 3D geological maps and models at a range of spatial scales. By adopting a more 'plug-and-play' approach, combined with geologists' knowledge, the conventional vector-based maps and models' approach could be significantly shortened, reducing time and resources required to generate bespoke 3D geological information. Additional benefits to this approach would be the ability to be able to more effectively (and numerically) communicate uncertainty in our maps and models.

4.5 SUMMARY AND NEXT STEPS

- BGS employs both 'litho-genetic' and 'morpho-genetic' approach to stratigraphic characterisation within the Quaternary and these underpin both our mapping and modelling approaches. Collectively, these approaches provide a relatively low-level of characterisation which is invariably highly generalised and does not effectively communicate information that relates to spatial variability, heterogeneity and local-scale detail.
- This level of characterisation is adequate for regional-scale characterisation and there is still a stakeholder demand for this information to be regularly updated. However, stakeholders also require higher-resolution detail, conceptual knowledge and information relating to spatial variability, heterogeneity and local-scale detail – specifically, insight into features of interest that may pose a geological risk.
- An alternative stratigraphic methodology, which we recommend would more effectively link mapping and modelling environments, incorporates elements of 'allostratigraphy', 'architectural elements analysis' and 'glacial landsystems' approaches. This hybrid stratigraphic approach focusses on establishing a hierarchical framework of both the bounding surfaces and geological / geomorphological units themselves. The benefit of this approach is that it enables the stratigraphic model to be more scientifically robust, contain more geological detail and information and use conceptual understanding to extrapolate the stratigraphy into data poor areas.
- We recommend the adoption of this approach to mapping and modelling the Quaternary, as part of a three-tiered approach to tackling the Quaternary. In addition to refining our approach to mapping and modelling, we also recommend the continued evolution of 'Quaternary Domains' as a high-level communication tool to support stakeholder engagement; and the requirement for spatial database (e.g. the 'Quaternary Data Matrix' or similar) as a baseline database of shallow sub-surface spatial data and information.
- The purpose of the 'Quaternary Data Matrix' is to be a 3D data matrix that extends across the zone of geology between the ground and rockhead surfaces. The matrix is intended to be a database of captured Quaternary data and information with individually blocks (and groups of blocks) that can be parametrised and populated with a range of point- and area-based geological, applied and interpreted information. A key aspect of this approach will be its flexibility, both in terms of scale and being able to be updatable manually and automatically, and that the structure and format of the data will be interoperable with other digital workflows and systems (e.g. 3D geological modelling, numerical modelling, machine learning etc).
- Work on the Quaternary Domains currently forms a major component of the UK Quaternary project work programme, and this will continue over the next few years; work will also commence on other aspects of this three-tiered workflow including an exercise to prioritise the technical content of the 'Quaternary Data Matrix'; we will also seek opportunities to utilise the 'architectural elements analysis' approach and test it within different Quaternary contexts.

5 Summary and Recommendations

- The Quaternary is one of the most important aspects of the UK geological record. This is because the shallow sub-surface has either been concealed by a veneer of Quaternary sediments or has been deformed by processes that operated during the Quaternary. The shallow sub-surface equates to the part of the geological record that humans interact with most frequently for societal and economical gain.
- Most of BGS's key stakeholders fall within 5 sectors: (1) local government, councils and authorities; (2) asset managers; (3) resource managers; (4) construction; and (5) academic and researchers. Each of these 5 sectors utilise parts of the shallow sub-surface that have been impacted by the Quaternary and there is an increasing demand to more effectively characterise at multiple scales this part of the geological record, to identify geological risks and provide information and knowledge that supports stakeholders in planning and decision making.
- BGS has a long tradition of studying and characterising the Quaternary geology of the UK. This has been underpinned by peer-reviewed science, commissioned research, published geological maps and most recently published 3D geological models. However, there is a growing awareness that the geology of the Quaternary is highly complex and variable, and that current mapping and modelling practices do not effectively capture and communicate this information.
- We therefore recommend that our corporate approach to characterising the Quaternary evolves, building on current knowledge, data and skills where possible but also utilising new digital data and techniques that enable the geology and landscape to be characterised more quantitatively. At a high-level, our aim is to further develop and modernise the Quaternary Domains concept as a communication tool for characterising the Quaternary as a high-level national scale. We also recognise that they way that the Quaternary has traditionally been characterised for the purpose of our geological maps and 3D geological models needs to evolve to meet ongoing scientific developments and stakeholder need. This is to ensure that as geologists, we are able to develop a robust geological framework that communicates the complexity and related risks of the Quaternary geological record more effectively.
- Finally, to support a quicker, more flexible and geologically robust and map and model production workflow, there is a requirement to evolve how Quaternary-related data is stored and managed. We therefore propose, the development of the Quaternary Data Matrix or a similar type of spatial dataset – a 3D matrix of information and data that is interoperable with corporate datasets and modelling platforms.

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://envirolib.apps.nerc.ac.uk/olibcgi.

ALDISS, D T, BLACK, M G, ENTWISLE, D C, PAGE, D P, AND TERRINGTON, R L. 2012. Benefits of a 3D geological model for major tunnelling works: an example from Farringdon, east–central London, UK. *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 45, 405-414. 10.1144/qjegh2011-066

BENN, D, AND EVANS, D J A. 2014. *Glaciers and glaciation*. (London: Routledge.) ISBN 1444128396

BOOTH, K A, BOOTH, S J, AND SLATER, C. 2010. BGS Geological Cross Sections & Quaternary Domains: User Guidance Notes. *British Geological Survey*, Open Report OR/10/030 (Keyworth), 36.

BOOTH, S, MERRITT, J, AND ROSE, J. 2015. Quaternary Provinces and Domains – a quantitative and qualitative description of British landscape types. *Proceedings of the Geologists' Association*, Vol. 126, 163-187. https://doi.org/10.1016/j.pgeola.2014.11.002

BOWEN, D Q. 1999. *A revised correlation of Quaternary deposits in the British Isles*. Geological Society Special Report No. 23. (London: Geological Society.)

BOYCE, J I, AND EYLES, N. 2000. Architectural element analysis applied to glacial deposits: internal geometry of a late Pleistocene till sheet, Ontario, Canada. *Geological Society of America Bulletin*, Vol. 112, 98-118.

BRICKER, S H, BARRON, A J M, HUGHES, A G, JACKSON, C, AND PEACH, D. 2014. From geological complexity to hydrogeological understanding using an integrated 3D conceptual modelling approach–insights from the Cotswolds, UK. 99-114 in *Fractured Rock Hydrogeology*. SHARP, J M (editor). (London: CRC Press.)

BURKE, H F, MORGAN, D J, KESSLER, H, AND COOPER, A H. 2009. A 3D geological model of the superficial deposits of the Holderness area. Commissioned Report CR/09/132. *British Geological Survey* (Keyworth), 58.

CHAPPELL, J, AND SHACKLETON, N J. 1986. Oxygen isotopes and sea level. *Nature*, Vol. 324, 137-140.

DEPT.FOR.TRANSPORT. 2019. Rail Factsheet, Department for Transport, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/851082/rail-factsheet-2019.pdf 6.

DOCHARTAIGH, B Ó, BONSOR, H, AND BRICKER, S. 2017. Improving understanding of shallow urban groundwater: the Quaternary groundwater system in Glasgow, UK. *Earth and Environmental Science Transactions of The Royal Society of Edinburgh*, Vol. 108, 155-172.

EL FELS, A E A, AND EL GHORFI, M. 2022. Using remote sensing data for geological mapping in semi-arid environment: a machine learning approach. *Earth Science Informatics*, Vol. 15, 485-496. 10.1007/s12145-021-00744-w

EVANS, D J A. 2003. *Glacial Landsystems*. (London: Arnold.)

EVANS, D J A, AND BENN, D (editors). 2021. *A Practical Guide to the Study of Glacial Sediments (Second Edition)*. (London: Quaternary Research Association.)

FORD, J, MATHERS, S, ROYSE, K, ALDISS, D, AND MORGAN, D J R. 2010. Geological 3D modelling: scientific discovery and enhanced understanding of the subsurface, with examples from the UK. *Zeitschrift der Deutschen Gesellschaft fur Geowissenschaften*, Vol. 161, 205-218.

GIBBARD, P L, HEAD, M J, WALKER, M J, AND STRATIGRAPHY, S O Q. 2010. Formal ratification of the Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma. *Journal of Quaternary Science*, Vol. 25, 96-102.

GILES, D P, MARTIN, C J, AND WILLIAMS, R B G. 2017. Engineering geology of the Quaternary. *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 50, 369-378. doi:10.1144/qjegh2017-104

HEINZ, J, AND AIGNER, T. 2003. Hierarchical dynamic stratigraphy in various Quaternary gravel deposits, Rhine glacier area (SW Germany): implications for hydrostratigraphy. *International Journal of Earth Sciences*, Vol. 92, 923-938.

HENGL, T, MILLER, M A, KRIŽAN, J, SHEPHERD, K D, SILA, A, KILIBARDA, M, ANTONIJEVIĆ, O, GLUŠICA, L, DOBERMANN, A, AND HAEFELE, S M. 2021. African soil properties and nutrients mapped at 30 m spatial resolution using two-scale ensemble machine learning. *Scientific Reports*, Vol. 11, 1-18.

HUGHES, P D. 2010. Geomorphology and Quaternary stratigraphy: the roles of morpho-, litho-, and allostratigraphy. *Geomorphology*, Vol. 123, 189-199.

KEARSEY, T, WILLIAMS, J, FINLAYSON, A, WILLIAMSON, P, DOBBS, M, MARCHANT, B, KINGDON, A, AND CAMPBELL, D. 2015. Testing the application and limitation of stochastic simulations to predict the lithology of glacial and fluvial deposits in Central Glasgow, UK. *Engineering Geology*, Vol. 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, AND CAMPBELL, S D G. 2017. 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*, Vol. 108, 123-140. 10.1017/S1755691018000270

KESSLER, H, AND MATHERS, S. 2004. Maps to models. *Geoscientist*, Vol. 14, 4-6.

KESSLER, H, MATHERS, S, AND SOBISCH, H G. 2009. The capture and dissemination of integrated 3D geospatial knowledge at the British Geological Survey using GSI3D software and methodology. *Computers and Geosciences*, Vol. 35, 1311-1321. 10.1016/j.cageo.2008.04.005

KNILL, J. 2003. Core values: the first Hans-Cloos lecture. *Bulletin of Engineering Geology and the Environment*, Vol. 62, 1-34.

LEE, J. 2018. Chapter 11: Glacial lithofacies and stratigraphy. 377-429 in *Past Glacial Environments*. MENZIES, J, VAN DER MEER, J.J.M. (editor). (Elsevier.)

LEE, J R. 2017. Crag Basin Rockhead Coding: metadata report. *British Geological Survey*, Internal Report IR/17/042 (Keyworth), 25.

LELLIOTT, M R, CAVE, M R, AND WEALTHALL, G P. 2009. A structured approach to the measurement of uncertainty in 3D geological models. *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 42, 95-105. 10.1144/1470-9236/07-081

LISIECKI, L E, AND RAYMO, M E. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records. *Paleoceanography*, Vol. 20.

MARTIN, C J, MORLEY, A L, AND GRIFFITHS, J S. 2017. Chapter 1: Introduction to engineering geology and geomorphology of glaciated and periglaciated terrains. 1-30 in *Engineering Geology and Geomorphology of Glaciated and Periglaciated Terrains*. GRIFFITHS, J S, AND MARTIN, C J (editors). *Geological Society, London, Engineering Geology Special Publications,* 28. (London: Geological Society of London.)

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

MCDOWELL, P W, BARKER, R D, BUTCHER, A P, CULSHAW, M G, JACKSON, P D, MCCANN, D M, SKIPP, B O, MATTHEWS, S L, AND ARTHUR, J C R. 2002. The Conceptual Ground Model. 51-59 in

Geophysics in Engineering Investigations. *Geological Soceoty, Engineering Geology Special Publications,* 19. (London: Geological Society of London.)

McMillan, A A. 2002. Onshore Quaternary geological surveys in the 21st century—a perspective from the British Geological Survey. *Quaternary Science Reviews*, Vol. 21, 889-899. https://doi.org/10.1016/S0277-3791(01)00064-6

McMillan, A A, Hamblin, R J O, and Merritt, J W. 2011. A lithostratigraphical framework for onshore Quaternary and Neogene (Tertiary) superficial deposits of Great Britain and the Isle of Man. *British Geological Survey*, IR/06/094 (Nottingham).

McMillan, A A, Heathcote, J A, Klinck, B A, Shepley, M G, Jackson, C P, and Degnan, P J. 2000. Hydrogeological characterization of the onshore Quaternary sediments at Sellafield using the concept of domains. *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 33, 301-323. 10.1144/qjegh.33.4.301

McMillan, A A, and Merritt, J W. 2012. A new Quaternary and Neogene Lithostratigraphical Framework for Great Britain and the Isle of Man. *Proceedings of the Geologists' Association*, Vol. 123, 679-691. http://dx.doi.org/10.1016/j.pgeola.2012.05.007

McMillan, A A, and Powell, J H. 1999. BGS rock classification scheme. Volume 4, classification of artificial (man-made) ground and natural superficial deposits : applications to geological maps and datasets in the UK. *British Geological Survey*, RR/99/044 (Nottingham), 65.

Merritt, J, Loughlin, S, Whitbread, K, and Terrington, R L. 2012. Model Metadata Report for Central Glasgow GSI3d Model. Internal Report IR/12/032. *British Geological Survey* (Edinburgh), 29.

Miall, A D. 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. *Earth-Science Reviews*, Vol. 22, 261-308.

Mielby, S, Eriksson, I, Campbell, D, de Beer, J, Bonsor, H, Le Guern, C, van der Krogt, R, Lawrence, D, Ryżyński, G, and Schokker, J. 2016. Opening up the subsurface for the cities of tomorrow Considering access to subsurface knowledge–Evaluation of practices and techniques. *COST*, 120.

Mielby, S, Eriksson, I, Diarmad, S, Campbell, G, and Lawrence, D. 2017. Opening up the subsurface for the cities of tomorrow The subsurface in the planning process. *Procedia Engineering*, Vol. 209, 12-25. https://doi.org/10.1016/j.proeng.2017.11.125

Mitchell, G F, Penny, L F, Shotton, F, and West, R G. 1973. *A Correlation of Quaternary deposits in the British Isles*. Geological Society of London, Special Report No. 4. (London: Geological Soceity of London.)

Moore, R, Fish, P, Trinder, S, Czarnomski, C, Dabson, O, and Fitzgerald, R. 2022. Engineering Geomorphology of HS2: Management of Geohazards. *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 55, qjegh2021-2122. 10.1144/qjegh2021-122

MPA. 2016. Long-term aggregates demand & supply scenarios 2016-2030. *Mineral Products Association* (London), 12.

NAU. 2020. Water supply and demand management. *National Audit Office* (Department for Environment, Food & Rural Affairs), 11.

Ogg, J G, and Pillans, B. 2008. Establishing Quaternary as a formal international Period/System. *Episodes*, Vol. 31, 230.

ONS. 2022. National Population Projections: 2020-based interim. 14.

Power, C, Mian, J, Spink, T, Abbott, S, and Edwards, M. 2016. Development of an Evidence-based Geotechnical Asset Management Policy for Network Rail, Great Britain. *Procedia Engineering*, Vol. 143, 726-733. https://doi.org/10.1016/j.proeng.2016.06.112

Power, C M, Patterson, D A, Rudrum, D M, and Wright, D J. 2012. Geotechnical asset management for the UK Highways Agency. *Geological Society, London, Engineering Geology Special Publications*, Vol. 26, 33-39. 10.1144/egsp26.5

RÄSÄNEN, M, AURI, J, HUITTI, J, KLAP, A, AND VIRTASALO, J. 2009. A shift from lithostratigraphic to allostratigraphic classification of Quaternary glacial deposits. *Gsa Today*, Vol. 19, 4-11.

RINGROSE, P S, MARTINIUS, A W, AND ALVESTAD, J. 2008. Multiscale geological reservoir modelling in practice. 123-134 in *The Future of Geological Modelling in Hydrocarbon Development*. ROBINSON, A, GRIFFITHS, P, PRICE, S, HEGRE, J, AND MUGGERIDGE, A (editors). *Geological Society, London, Special Publications,* 309. (Geological Soceity: London.)

ROSE, J. 1989. Stadial type sections in the British Quaternary. 15-20 in *Quaternary Type Sections: imagination or reality?* ROSE, J, AND SCHLUCTER, C (editors). (Rotterdam: Balkema.)

ROSE, J, AND MENZIES, J. 2002. Glacial Stratigraphy. 445-473 in *Modern and Past Glacial Environments*. MENZIES, J (editor). (Amsterdam: Elsevier.)

ROSE, J, AND SCHLÜCHTER, C. 1989. *Quaternary type sections : imagination or reality?* (Brookfield, Vt.: A.A. Balkema.) ISBN 9061917344

RUSSELL, C. 2019. Climate Change Risks for London - a review of evidence under 1.5˚C and different warming scenarios. *Jones Climate Sustainability Consulting* (London), 30.

RUTTER, H, CUNNINGHAM, J, JACKSON, C, AND LEWIS, M. 2006. Hydrogeological parameterisation of the Thames Gateway GSI3D model. *British Geological Surevy* (Wallingford), 42.

SANG, X, XUE, L, RAN, X, LI, X, LIU, J, AND LIU, Z. 2020. Intelligent high-resolution geological mapping based on SLIC-CNN. *ISPRS International Journal of Geo-Information*, Vol. 9, 99.

SHACKLETON, N J. 1987. Oxygen isotopes, ice volume and sea level. *Quaternary Science Reviews*, Vol. 6, 183-190.

SLOMKA, J, AND EYLES, C. 2013. Characterizing heterogeneity in a glaciofluvial deposit using architectural elements, Limehouse, Ontario, Canada. *Canadian Journal of Earth Sciences*, Vol. 50, 911-929.

SLOMKA, J M, AND EYLES, C H. 2015. Architectural–landsystem analysis of a modern glacial landscape, Sólheimajökull, southern Iceland. *Geomorphology*, Vol. 230, 75-97. https://doi.org/10.1016/j.geomorph.2014.11.006

SLOMKA, J M, EYLES, C H, MULLIGAN, R P, MCKAY III, E D, AND BERG, R C. 2015. Internal architecture of a till sheet, Tiskilwa Formation, north-central Illinois, USA: Application of architectural element analysis. *Sedimentology*, Vol. 62, 1328-1359.

SPINK, T. 2020. Strategic geotechnical asset management. *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 53, 304-320.

STAFLEU, J, MALJERS, D, GUNNINK, J, MENKOVIC, A, AND BUSSCHERS, F. 2011. 3D modelling of the shallow subsurface of Zeeland, the Netherlands. *Netherlands Journal of Geosciences*, Vol. 90, 293-310.

STOKER, M S, BALSON, P S, LONG, D, AND TAPPIN, D R. 2011. An overview of the lithostratigraphical framework for the Quaternary deposits on the United Kingdom Continental Shelf. *British Geological Survey* (Edinburgh), 40.

SULLIVAN, T D. 2010. The geological model. 155-170 in *'Geologically Active'. Proceedings of the 11th Congress of the International Association for Engineering Geology and the Environment* WILLIAMS, A L, PINCHES, G M, CHIN, C Y, MCMORRAN, T J, AND MASSEY, C I (editors). (Auckland, New Zeland: CRC Press.)

TW. 2014. Thames Water: Final Water Resources Management Plan 2015-2040 - Main Rpeort. *Thames Water* (Reading).

WALTON, G, AND LEE, M K. 2001. Geology for our diverse economy: report of the Programme Development Group for Onshore Geological Surveys. *British Geological Survey* (Keyworth, Nottingam).

ZACHOS, J, PAGANI, M, SLOAN, L, THOMAS, E, AND BILLUPS, K. 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. *science*, Vol. 292, 686-693.