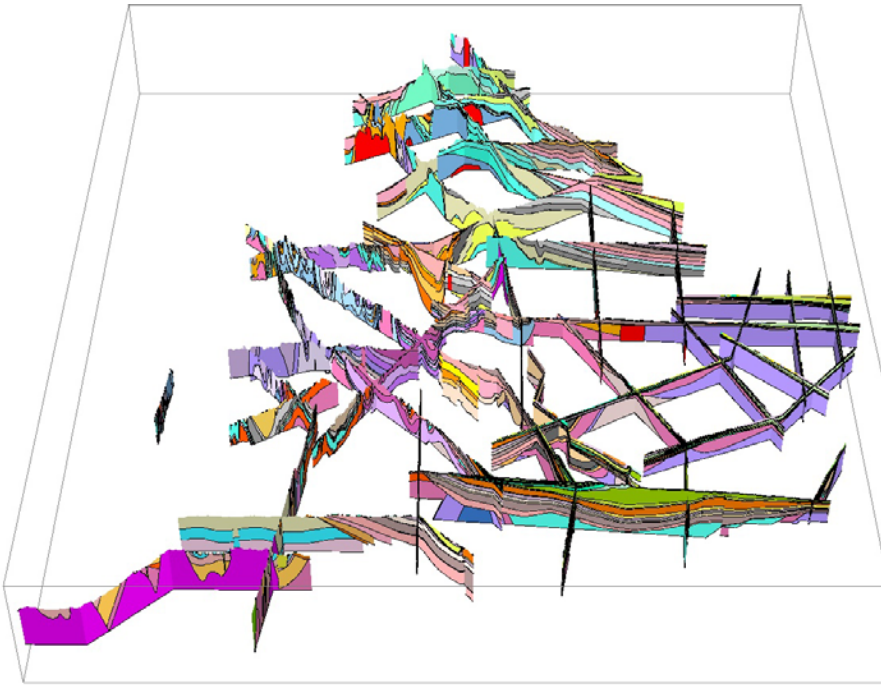
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

A geological fence diagram for England and Wales

Geology and Landscape Programme

Open Report OR/12/081



BRITISH GEOLOGICAL SURVEY

GEOLOGY AND LANDSCAPE PROGRAMME

BGS OPEN REPORT OR/12/081

A geological fence diagram for England and Wales

D I Schofield, K Ambrose, A J M Barron, P M Hopson, S J Mathers, A H Myers, C N Waters, R L Terrington

Keywords

Fence diagram England Wales

Front cover

The geological fence diagram for England and Wales.

Bibliographical reference

Schofield, D.I., Ambrose, K. Barron, A.J.M., Hopson P.M. Mathers S.J., Myers A.H., Waters C.N. & Terrington R. 2012. A geological fence diagram for England and Wales. British Geological Survey Report, OR/12/081. 33pp.

Keyworth, Nottingham British Geological Survey 2012

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 the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

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

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

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

Contents

Summary

This report contains a brief description of the data and methodology used to compile the National Geological Fence Diagram (NGFD). The NGFD comprises a network of intersecting geological cross-sections covering England and Wales, to a minimum depth of 1 km and a total section length of approximately 5,500 km. It was compiled by the British Geological Survey (BGS) on behalf of the Environment Agency (EA) and is based upon lines of section agreed between both parties at the inception of the project. The model includes generalised bedrock strata based principally on the BGS 1:625 000 scale digital geological data and superficial deposits greater than 10m in thickness. Additional sources of model data were also considered, largely taken from published BGS data holdings. In total 41 cross-sections were constructed and geologically correlated within the GSI3D software.

1 Introduction

On the instruction of the Environment Agency (EA) the British Geological Survey (BGS) produced a fence diagram of intersecting cross-sections covering England and Wales, to a minimum depth of 1 km and a total section length of approximately 5,500 km. The ‘National Geological Fence Diagram’ (NGFD) is based upon lines of section agreed between BGS and the EA. Individual sections are based on specified baseline data as well as additional sources of model data (see below). In total 41 cross-sections (36 specified by the Environment Agency plus an additional 5 in South East England) were constructed and geologically correlated within the GSI3D software (Figure 1).

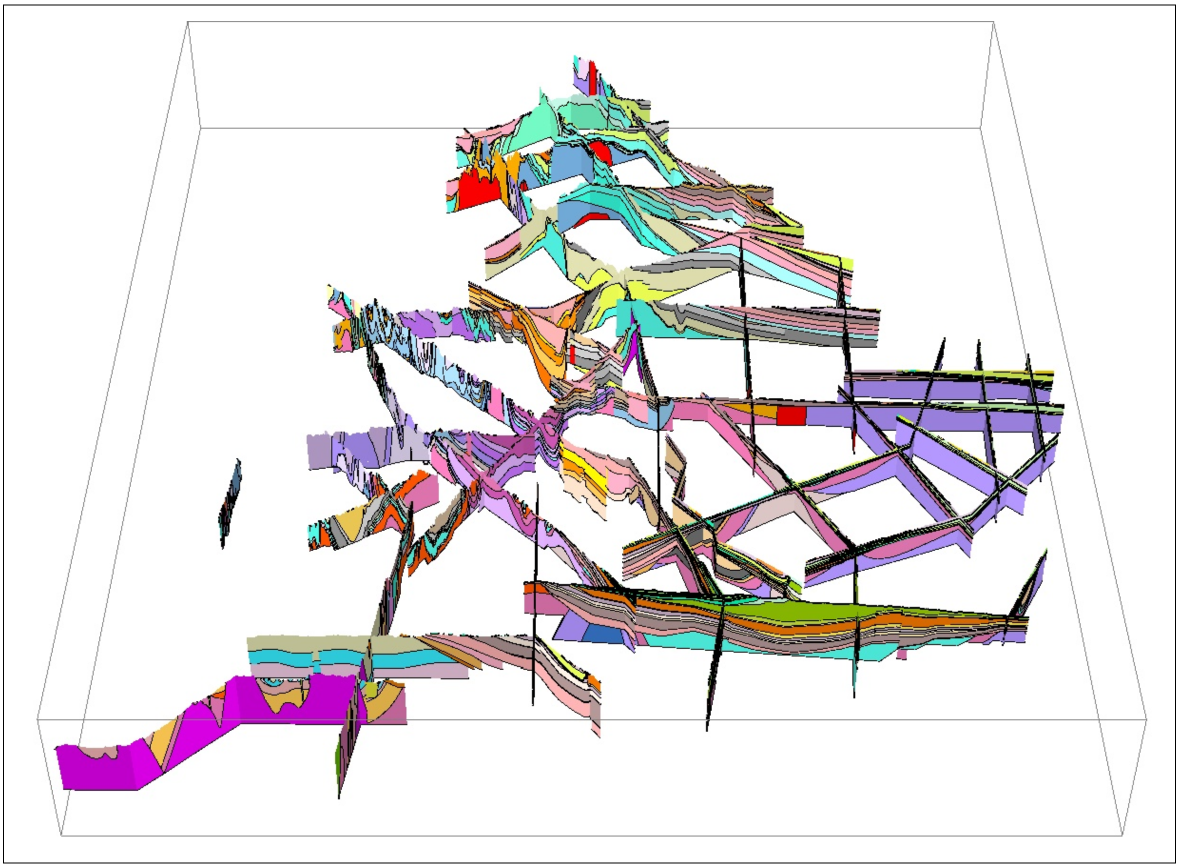


Figure 1. NGFD correlated sections

2 Baseline Data

Individual horizontal sections that make up the NGFD are based principally on the 2007 BGS 1:625 000 scale bedrock geology dataset (Figure 2). The digital map data and polygon attributes have formed the basis on which individual geologist's have interpreted the sub-surface projection for each section and have also provided the basis for the, largely Group level, lithostratigraphic subdivisions represented in the legend of the NGFD.

Figure 2 Printed version of the BGS 1:625 000 scale geological mapsheet data

Limitations of the data

It should be understood that the 1:625 000 scale dataset represents a considerable simplification, both in terms of lithostratigraphy, geological line-work and the representation of faults, from the standard BGS 1:50 000 scale DiGMapGB-50 digital geological map series and should not be considered as the most detailed or accurate geological map data held by the BGS. The DiGMapGB-50 data is itself generalised from a variety of primary survey data including surface observations, collected typically at the 1:10 000 or 1:25 000 scales, combined with information derived from records of rock exposures, man-made excavations, boreholes, aerial photography, satellite imagery, geophysical and geochemical investigations. It should be noted here that, given the scope of this project, no new, previously unpublished surface or subsurface data was consulted in the compilation of the NGFD, although additional data from existing subsurface models was used by geologist's to make their interpretations (see below), and that the final model does not represent an interpretation of all the available data held by the BGS. It should also be noted that confidence and uncertainty are variable across the dataset as a whole. For instance in urban areas, areas of former deep mining or within the limits of major aquifers it should be expected that a higher density of subsurface data exists resulting in a better overall understanding of the geology. As this data is integral to the compilation of the primary survey, it can be expected that these areas may have a lower degree of uncertainty. By contrast, many rural areas outwith the limits of recent deep mining or exploitation as aquifers, such as much of Wales and the Lake District, may have sparse subsurface data and hence a higher degree of overall uncertainty.

Details of the methodology used in the compilation of the 1: 625 000 scale digital geological map are presented by Smith (2009).

Superficial Deposits

The NGFD sections depict a generalised representation of superficial deposits where they are both extensive and of a significant thickness (>10m). The critical areas that intersect individual sections are derived from the BGS Superficial Drift Thickness Model (SDTM). The SDTM is a mathematical model of the thickness of superficial deposits produced by analysing rock-head depths from approximately 600 000 borehole logs held in the BGS archives as well as the surficial extent of the deposits derived from DiGMapGB-50. The data are in the form of an interpolated grid with a resolution of 50 x 50 metres. Details of this model and its limitations are provided by Lawley & Garcia-Bajo (2010).

3 Additional Data

In order to interpret the subsurface geology in the NGFD sections, geologist's have consulted existing models of the 3D subsurface geology of England and Wales including syntheses of deep boreholes, seismic lines and geophysical data, largely presented in the BGS geology and subsurface geology memoir series, as well as other contoured and digital 3D model surfaces from the BGS data holdings and peer reviewed scientific papers. Where necessary, additional data materials were scanned and georeferenced in ArcGIS (ESRI®) for use in the digital modelling process.

4 Position of specific sections

The original project proposal illustrates a preliminary section plan submitted for discussion and agreement with the EA (Figure 3). Prior to the project start-up meeting, the EA project leader canvassed regional offices on the alignment of individual sections. Their responses resulted In a revised BGS plan for section alignment.

The changes agreed upon, based on balancing the requirement of the regional offices against the overall value of the project are illustrated in the final section plan (Figure 4). Those changes not enacted were largely rejected in order to keep the overall section length within the overall project budget. The principal changes are as follows:

1. Wales: realignment of E-oriented section over the S Wales coalfield to a more cross-strike position.
2. Midlands: minor realignments as requested.
3. North –East: minor realignments as requested.
4. Southern: new section through east Kent inserted
5. Thames: major realignment of principal sections as requested.

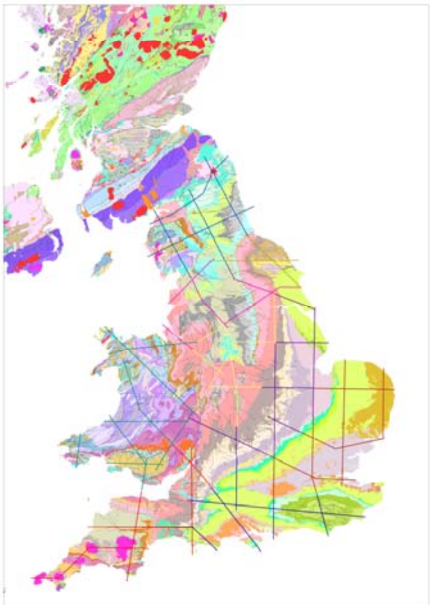


Figure 3. Proposed section plan prior to EA consultation

Figure 4. EA agreed lines of section.

5 Methodology

This section presents a more detailed account of the methodology including a description of the workflow developed for the project.

Workflow

A linear workflow (Figure 5) was devised for the compilation of the NGFD sections and overall 3D model; some of the points are described in more detail in the subsequent account:

1. Individual sections were assigned to geologists with relevant local expertise (Table 1, Figure 6).
2. Each geologist identified all additional resources from their expert knowledge of BGS and other publications.
3. A Geological Vertical Sequence (Stratigraphy) was compiled based on the 625K map and formatted for use in GSI3D
4. IT specialists compiled baseline and additional data into individual GSI3D workspaces for each geologist containing individual sections to be modelled and existing data intersecting those lines of section.
5. The geologists produced a first iteration of sections, these were snap fitted to intersecting sections using GSI3D
6. Quality Assurance check of individual sections was performed by all the geologists to ensure consistency of style, classification and interpretation
7. Construction of cross-section fence diagram, amalgamation and fitting of individual sections
8. Production of a revised colour legend based on actual geological units represented on the sections.

9. Reporting.
10. Delivery.

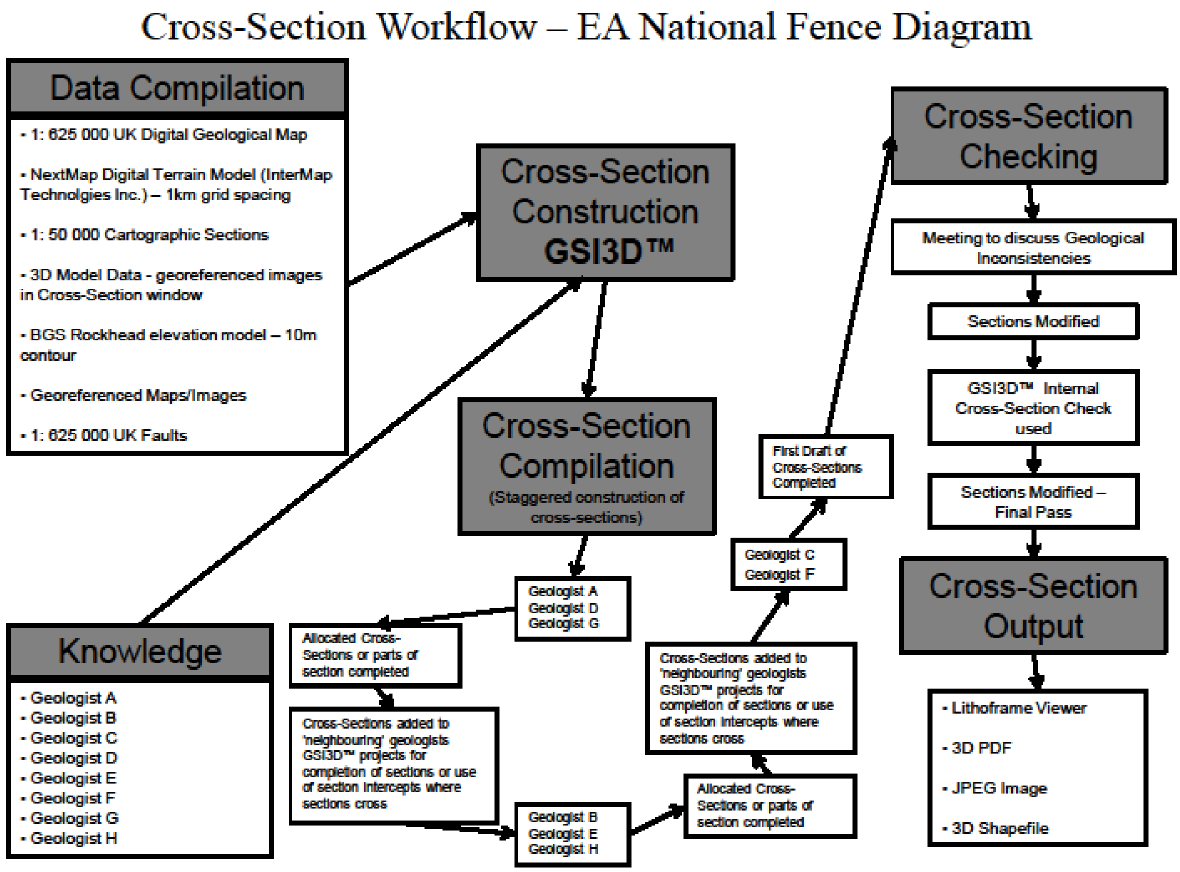


Figure 5. Schematic project workflow

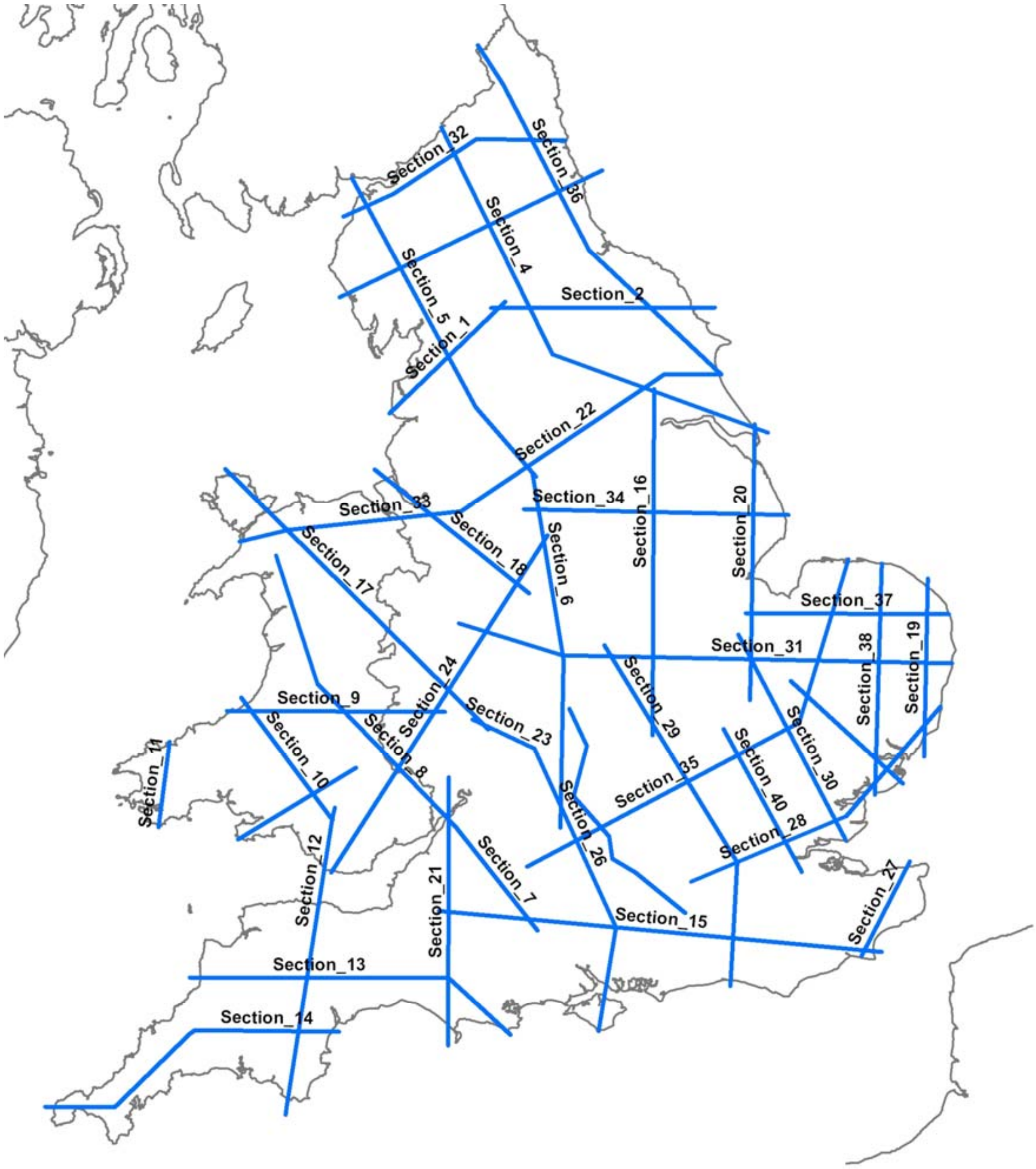


Figure 6. Key to numbered sections

Section Number	Pete Hopson	Mark Barron	Keith Ambrose	Colin Waters	Phil Wilby	Dick Crofts	Poul Strange	Steve Mathers	Dave Schofield
1						■			
2					■				
3				■					
4		■		■		■			
5				■		■			
6		■	■						
7	■						■		
8							■		■
9 -11									■
12							■		■
13	■						■		
14							■		
15	■								
16		■	■						
17									■
18			■			■			
19								■	
20		■							
21							■		
22			■			■			
23		■							
24			■						■
25									■
26	■	■							
27	■								
28								■	
29	■	■						■	
30								■	
31		■	■					■	
32				■					
33									■
34		■	■						
35	■							■	
36				■	■				
37 -41								■	

Table 1. Geologists responsible for cross- sections

GVS design

GSI3D requires the development of a unique Geological Vertical Sequence file (GVS), with all geological units listed in stratigraphic stacking order (see modelling methodology of Kessler et al., 2009). For the purposes of this study a unique GVS was devised based on the legend for the BGS 625k geological map to produce a specific GVS in which each uniquely coloured unit on the map face is identified and listed in order of its stratigraphic occurrence. A number of generalised codes were also generated to accommodate undivided or unknown strata in the subsurface where necessary. Igneous intrusions and volcanic rocks, largely indurated crystalline rocks of little importance as aquifers, were also generalised into a smaller number of subdivisions for simplicity. For the superficial deposits, a threefold subdivision was agreed with the Agency and applied. Deposits were classified as 'permeable', 'impermeable' and 'mixed'. Mixed units comprise heterogeneous deposits or complex successions in which there are complex relationships between permeable and impermeable horizons and it was not practicable these for modelling at the scale of this project.

Digital Modelling

The 3D geological model is based on the geological interpretation and correlation of cross-sections made by the user using the best available data and information. Geological cross-section construction for all of the cross-sections was carried out using GSI3D modelling software (Kessler *et al*, 2009). GSI3D allows several data sources to be viewed and visualised in the same spatial environment. These data sources include digital borehole data, Digital Terrain Models (DTMs), digital geological maps, geophysical sections, and georeferenced images to guide the construction of the cross-sections. A NEXTMap (Intermap Technologies Inc) 1km cell size DTM data was used to provide the top layer or "cap" to the cross-sections.

Existing 3D model data, described above, used in support of the geological interpretation, were imported into GSI3D and displayed as inactive synthetic lines as a back drop in cross-section. Each of the surfaces were labelled and saved out as a georeferenced snapshot of the cross-section as a JPEG. These could then be turned on and off and made transparent in cross-section during line correlation by the geologist (Figures 7, 8). This process ensured the consistency of interpretation with previous detailed geological modelling undertaken in England and Wales by BGS. Georeferenced images were imported into the 2D Map Window of GSI3D™ which has a live link to the Section Window so that geologist could relate the image data to the alignment and intersections with the cross-section. Horizontal sections from the 1:50 000 scale geological maps that intersected the specified sections were also added as intercepts to assist section construction. Similarly intersecting faults derived from the 1: 625 000 dataset were added to a depth of 1500m on the section, for the purposes of this modelling the faults are depicted as vertical planes. This is a reasonable depiction because most faults are close to vertical in the upper brittle part of the crust, although where seismic data is unavailable their true orientation is rarely determined. Exceptionally where significant low angle thrust faults are known from surveying, these were inserted manually to avoid geometrical problems at depth.

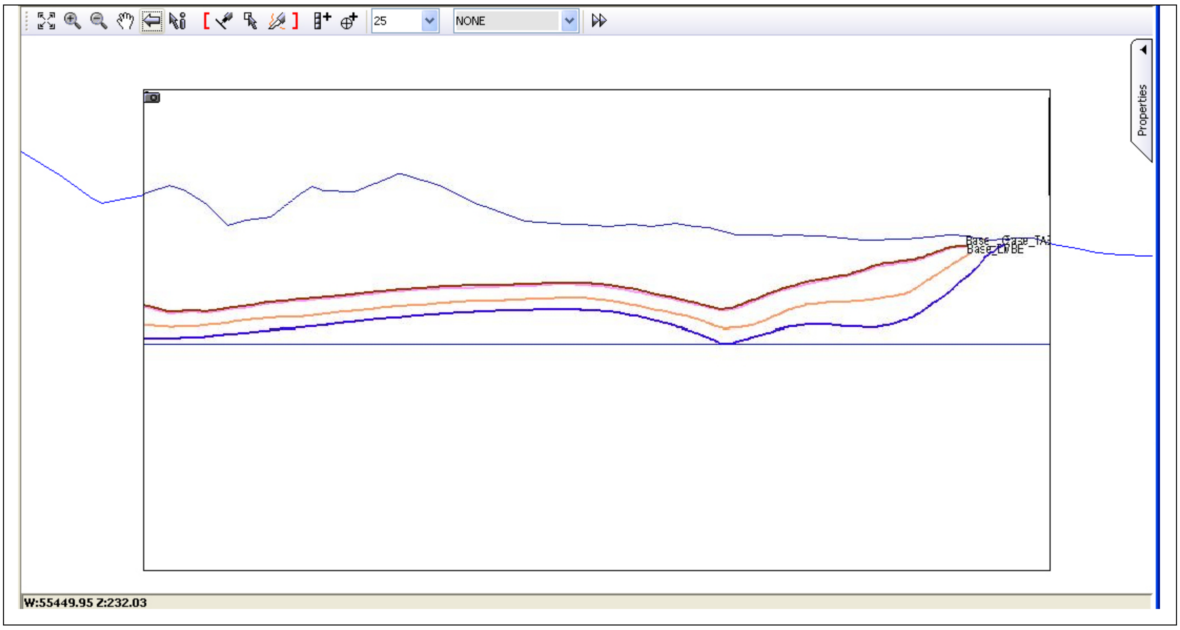


Figure 7. Section backdrop showing synthetic 3D model data

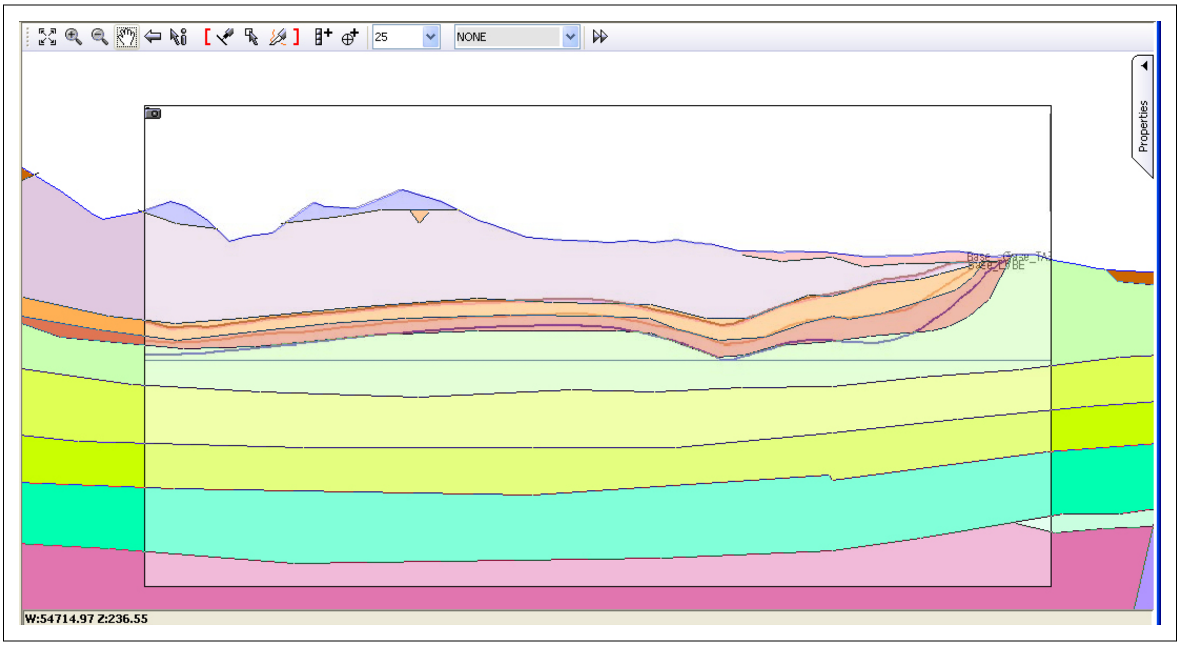


Figure 8. Section showing geologists' interpretation overlain by synthetic 3D model data

The BGS Rockhead (base of superficial geology) elevation model was used to define areas of greater than 10m of thickness of Quaternary superficial deposits. A derived 10m contour data set was added to each of the cross-sections and this was used as a guide to delineate the thickness of superficial deposits.

6 User guide

Each section comprises an interpretation made by a BGS geologist with experience working in the relevant part of the UK geological succession. Completing the final version of each section is an iterative process in which the geologist considers the available additional data and modifies, accepts or rejects it on the basis of its compatibility with the 625k dataset as well as their own personal experience in understanding stratigraphic and structural architecture across their specialist region and stratigraphic interval. Where individual sections were shared between two or more geologists, and where lines of section intersect, the final version represent a consensus agreed by the geologists concerned.

Given the nature of the primary and additional data sources consulted for this exercise it should be understood that the final model is largely schematic and that there are a number of limitations to the NGFD that are outlined here:

In many sections local generalisation is present where units are sub-divided in one part of the section and shown undivided elsewhere. This largely reflects the limitations of the available data and includes three scenarios:

a) Where detailed surface mapping cannot be extended into the subsurface with any degree of certainty. This applies to much of the older, Neoproterozoic and Lower Palaeozoic strata. In the case of the Neoproterozoic 'basement' outcrop is restricted and structurally complex, accordingly most Neoproterozoic lithologies are shown as a single undifferentiated unit. In the Lower Palaeozoic case, where the stratigraphy is well controlled at surface, such as in much of Wales, detailed subdivision has been achieved, however, where it is only known in the subsurface from a limited number of boreholes and seismic survey, such as under much of East Anglia, a generic subdivision has been employed. This scenario also locally applies to the Triassic strata, in particular the aquifer rocks of the Sherwood Sandstone Group are only shown subdivided into component groups where there is sufficient control (such as the Cheshire Basin). Another example of this is where generalisation has been applied to the thin Jurassic strata of the Great and Inferior Oolite groups which are only locally shown separately.

b) Where strata are subdivided in detail in the subsurface but shown greatly generalised at surface. This generally reflects where there is good control on the stratigraphy from detailed study of borehole data compared to the lack of a modern survey at surface. An example of this can be seen in the Cretaceous Chalk Group, the major aquifer of the London Basin. This has been shown subdivided into individual formations where known from subsurface data in Central London and parts of the London Basin, however it is shown more generalised at surface in the Chilterns and North Downs reflecting the fact that the primary surveys in these areas predate the modern subdivision of the Chalk into formations

.

c) Most of the sections have been constructed using a vertical exaggeration in order to provide a greater degree of precision for geologist's when estimating unit thickness and inclination in the subsurface. As a consequence of this some geometrical imprecision can be introduced, particularly where strata are folded. It is recommended that the NGFD is **viewed at a x 10-20 vertical exaggeration**

d) Bearing in mind that individual sections are largely interpretive and schematic, it is unlikely that bed thickness and depth to certain horizons are represented with a very high degree of accuracy. The digital formats in which the NGFD are delivered do not place any restriction on the degree to which users can zoom in to view or analyse the data. Users should be aware that by zooming in to a considerable amount particular an unrealistic impression of the overall accuracy could be gained and this should not be used to make detailed and localised prognoses of the subsurface geology. In summary **the intended resolution of the model corresponds to that of the 625K scale geological map**

e) The final sections are delivered in a numbers of formats:

- Cross-section 3D Shapefiles are delivered as individual sections and a combined model. These should be viewed using ESRI ArcScene software via the .lyr files (preferably version 9.3.1 in which the files have been tested). In this software, individual section attributes can be interrogated using the info tool. Attributes include the unit name, age and lithology as well as a unique code (in the format AZRU-GD where the first part of the code represents the lithostratigraphic unit and the second part a unique lithological identifier that can be related to BGS corporate databases).
- Individual and combined sections delivered in the 3D .pdf format are viewed using Adobe Reader software version 9 or later. In this format, section attributes can be viewed by first opening up the model tree. Individual section legends are also presented in pdf format. The combined model may take approximately 10 minutes to load.
- The data is also delivered bundled into the BGS LithoFrame Viewer using via the BGS extranet. In this software the Legend must be changed to the Text_strat option for sections to colour up with the schema used in the 625K mapsheets (default is Stratigraphy).
- Individual and combined sections are also delivered as images in the .jpg format. In this format, some sections are repeated at x10 and x20 vertical exaggeration.

7 Geological Description

The following account of the geology of England and Wales is pertinent to the 1:625 000 scale geological dataset and is largely derived from the sheet explanation associated with the litho-printed versions of the two mapsheets (Jackson, 2008; Stone, 2008).

Neoproterozoic rocks (1000 to 542 million years ago)

Neoproterozoic rocks are exposed at surface in Anglesey, Caernarvon and Lleyn in north-west Wales. In south-west Wales they are exposed around St David's Head and near Carmarthen. They also crop out in fault-bounded inliers across central England from Shropshire to Leicestershire and form much of the unexposed crystalline basement present at depth beneath England and Wales. The Neoproterozoic rocks are thought to represent relicts of ancient island arc volcanoes and flanking sedimentary basins as well as the deeply eroded remnants of igneous intrusions that formed during assembly of one of the earth's oldest supercontinents known as 'Gondwana'. On Anglesey (section 17) and Lleyn the Neoproterozoic rocks are low-lying in comparison with the adjacent terrain. But in England they stand proud of the softer rocks of the surrounding countryside and form distinctive steep-sided hills or ranges such as the Malvern Hills, Pontesford Hill, and The Wrekin near Shrewsbury, Hanter Hill near Kington (section 9) and Charnwood Forest in Leicestershire. The Neoproterozoic rocks predominantly comprise highly indurated crystalline igneous and metamorphic rocks. The metamorphic rocks are strongly contorted and preserve a long history of deformation. In most of the sections, Neoproterozoic rocks are shown on the NGFD sections as undivided.

Cambrian rocks (542 to 488 million years ago)

The largest region of exposed Cambrian rocks in southern Britain is found in north Wales (section 8, 33, 17). Cambrian strata also crop out at St David's Head in Pembrokeshire (see at depth in section 11), along the Welsh Borderlands at Shelve and from Telford to near Kington (section 31). They occur in the Midlands at Nuneaton as well as Charnwood Forest in Leicestershire, and are also proven at depth beneath part of England. The most southerly outcrop is in Cornwall where slivers of Cambrian strata are caught up within the Lizard Complex. Cambrian rocks are generally deformed and weakly metamorphosed; they are hard and indurated and locally preserve a planar parting or 'cleavage'.

A great thickness of Cambrian strata, derived from the ancient continent of Gondwana accumulated in sedimentary basins in north Wales. The succession is estimated at 3500m thick in the Bangor area and up to around 4000m farther south to the east of Harlech. In the Harlech area these are folded into a broad anticlinal structure cored at depth by Neoproterozoic volcanic rocks (section 8). In this area the succession comprises an Early Cambrian division, around 2000m in thickness, dominated by thick units of sandstone and subordinate mudstone deposited in a marine sedimentary basin. These are overlain by a Middle to Late Cambrian division, also around 2000m in thickness, dominated by black mudstone, locally with packets that are thinly interlayered with sandstone beds recording shallowing and pass up into rocks of earliest Ordovician (Tremadoc) age that were deposited in a near shore environment.

The Cambrian of the Bangor area comprises a contrasting succession of sandstone and conglomerate, up to around 1500m in thickness (section 33). The conglomerates are dominated by clasts of volcanic origin. These are thought to have been derived from a nearby contemporary volcanic centre, although the age of the deposit is not well constrained. The conglomerate and sandstone is overlain by around 900m of mudstone of Early Cambrian age. The Middle Cambrian of the Bangor area comprises around 400m of thick bedded sandstone and passes up into a Late Cambrian succession of thinly interbedded sandstone and mudstone, up to around 600m in thickness. The Cambrian rocks of the Bangor area are strongly folded and broadly form a faulted anticlinal structure cored by Neoproterozoic volcanic rocks exposed at surface.

A thinner, approximately 1100m, succession of Cambrian rocks exposed at St Tudwal's Peninsula on Lleyn closely resembles that of the Harlech area. In south Wales a similar pattern of sedimentation is preserved by a succession of marine sandstones of Early Cambrian age that pass upward into a Middle Cambrian sandstone of nearshore marine origin, in turn overlain by intertidal and marine mudstone and siltstone of Late Cambrian age.

On Anglesey, a thick succession of interbedded thick sandstone and mudstone, part of the Monian Supergroup, is thought to be of Late Cambrian age and passes up into schists and a chaotic 'mélange' unit that are thought to be of earliest Ordovician age (section 17). They are strongly folded and faulted and represent some of the most strongly metamorphosed rocks preserved in England and Wales. As a consequence, estimates of their thickness and interpretations of depositional environment have proven problematic. In the Welsh Borderland and English Midlands Cambrian sediments comprise sandstone and conglomerates that were deposited in shallow water that pass up into a mudstone dominated succession deposited in deeper water.

Ordovician rocks (488 to 444 million years ago)

Ordovician rocks are widely distributed in England and Wales, with large area of outcrop in the Lake District and Wales and scattered inliers across the West Midlands, as well as being proven in the subsurface beneath parts of England.

The Ordovician rocks record a history of basin subsidence, sedimentary deposition and volcanism associated with subduction of an oceanic crustal plate beneath the margin of Gondwana. Most of the rocks are tough and indurated, weakly metamorphosed and deformed.

Relicts of volcanic centres are preserved in most areas of Ordovician rock. The oldest of these is of earliest Ordovician (Tremadoc) age and is preserved near Dolgellau in north Wales (section 8). Associated Tremadocian sedimentary rocks generally comprise thick bedded sandstone and mudstone, up to around 350m in thickness, and conformably overlie the Late Cambrian succession. Strata of Tremadoc age are also exposed in the

Welsh Borderland, near Shelve (section 17) and are proven in the subsurface in the English Midlands where up to 2000m are present beneath the Worcester Basin.

Following a short-lived episode of uplift and erosion, a sedimentary succession of middles Ordovician age (Arenig) was deposited across Wales and the West Midlands, unconformably overlying older strata of Tremadoc, Cambrian and Neoproterozoic age. The earliest Arenig strata comprise thick bedded sandstones and conglomerate deposited in a shoreface environment marking marine transgression and the onset of renewed basin subsidence. These pass up into thinly bedded, shallow-marine, bioturbated sandstones and mudstones. Together the Arenig sedimentary succession is up to around 300m in thickness. Interleaved with the Early Ordovician sandstones and mudstones are strata that were clearly derived from a volcanic source. Indeed the Arenig sandstones pass up into a succession of interleaved volcanic and sedimentary rocks that were deposited through Llanvirn and Caradoc times. To the northwest of these, on Anglesey, a poorly understood succession of Arenig and younger Ordovician strata are preserved (section 17); the upper part of which preserves folded early Silurian strata, host to the historically important mine workings at Parys Mountain.

The Llanvirn succession of north Wales comprises up to around 1000m of mudstone interleaved with units of volcanic rock. Similar successions of interlayered volcanic units and mudstones are exposed near Shelve (section 17), Builth Wells (section 9) and in north Pembrokeshire (section 11). In contrast, the Llanvirn succession exposed around Llandeilo in Carmarthenshire contains relatively little volcanic material. Here, around 700m of marine mudstones pass up into a succession of thick bedded sandstones and flaggy, interbedded sandstone and mudstone, up to around 900m thick, that record deposition in a shallow marine, shelf environment. In the Lake District equivalent rocks of Tremadoc to Llanvirn age comprise up to 5000m of mudstone with scattered units of sandstone (section 5).

In north Wales, the overlying Caradoc succession comprises up to around 3000m of marine mudstone with scattered sandstone units and units of volcanic rocks that locally make up around 50% of the succession (section 17, section 33). The volcanic rocks are resistant to weathering and have a strong topographic expression in the mountains of the Snowdonia. A similar succession of interlayered volcanic rocks and marine mudstones, up to 6000m in thickness is preserved in the southern part of the Lake District (section 3, 5). By contrast, in central Wales the Caradoc succession is thinner, up to around 700m, contains only sparse, thin volcanic horizons and largely comprises mudstones with subordinate units of sandstone deposited in a deep marine setting. A thinner Caradoc succession, up to 150m thick, is exposed further south between Llandeilo and Carmarthen and at Caradoc in Shropshire. This succession marks the eastern limit of the Lower Palaeozoic Welsh Basin and preserves mudstone, thin sandstone beds and units of limestone deposited in a shallow marine, shelf setting.

The division between broadly shelf sedimentation and basinal sedimentation is carried through in the overlying Ashgill strata of Wales and the Welsh Borderland. At this time global fall in sea-level in response to the growth of glaciers led to rapid deposition of a thick Ashgill succession in central Wales, comprising around 2500m of bioturbated or slumped and destratified mudstone with scattered units of thick bedded sandstone (section 9,10). By contrast, the Ashgill of the Lake District (section 5) comprises a considerably thinner, less than 100m succession of predominantly calcareous siltstone and muddy limestone. These were deposited in shallow water conditions and attest to globally low sea-levels at that time.

Silurian rocks (444 to 416 million years ago)

Silurian strata are exposed in the southern part of the Lake District (section 5) and much of Wales (e.g. sections 8, 9, 10, 33), with small inliers north of Bristol (close to the line of sections 7, 21) and along the Malvern Lineament (section 17). In the Midlands the Silurian crops out at Walsall and near Dudley (section 31). In Wales and the Lake District Silurian sedimentary rocks are deformed and weakly metamorphosed; few volcanic rocks are recorded. The Silurian succession records the final stages of amalgamation of Gondwana with the palaeo-continent of Laurentia that began with oceanic subduction during the Ordovician. Deposition during the Silurian was also influenced by a gradual rise in sea level that followed the melting of the late Ordovician glaciers.

During the Silurian, the English Midlands and Welsh Borderland, extending into Pembrokeshire, formed an area of low relief, known as the Midland Platform, that was gradually submerged remaining as a shallow water shelf. Seismic data suggest that Silurian rocks underlie Triassic strata between the North and South Staffordshire coalfields (e.g. section 24), as well as Mesozoic strata of eastern England (section 31), but are absent from a large area to the south-east of the Birmingham Fault (section 6) thus effectively defining the edges of the Midland Platform. Silurian rocks are recorded at depth in East Anglia. The Silurian succession of the Midland Platform comprises interlayered units of mudstone sandstone and limestone. The overall thickness variation of this succession is poorly understood. In places the Silurian succession of this region is relatively thin, recording only several hundred metres of strata. Elsewhere, deep fault-bounded basins developed during the early Silurian, preserving up to around 4000m of sediments.

To the west of the Midland Platform in central and north Wales, up to around 4000m of sediment accumulated in a region of enhanced basin subsidence, , generally in a deep-water marine setting, known as the Welsh Basin. These comprise a succession of interlayeyed, thick units of sandstone-dominated and mudstone dominated composition. In the Lake District, an equivalent succession of Silurian basinal strata, up to around 4000m thick also comprises interlayered, thick units of sandstone-dominated and mudstone-dominated lithologies.

During Ludlow and Pridoli times, the depositional environment became shallower and basin inversion eventually led to uplift, erosion and deposition of continental red beds. Most of this facies is of Devonian age, but the lower parts are of latest Silurian (Pridoli) age. The base of the succession comprises distinctive units of sandstone, up to 50m thick that were deposited in shallow marine, nearshore conditions. These pass upward into a succession of red mudstones and thin sandstone beds, deposited in a tidal flat setting that mark the onset continental conditions across much of southern Britain.

Volcanic rocks of Silurian age are found in south Wales. The Skomer Volcanic Group in Pembrokeshire consists of mafic lava flows that were extruded on land, and occur with breccias and sedimentary rocks. Eastwards at Maesteg, rocks of similar composition have been found in a borehole, and cobbles of similar volcanic material are found in the Devonian conglomerate between Bridgend and Cardiff. Lavas are also found in the Tortworth inlier near Bristol and in the Mendips.

Devonian rocks (416 to 359 million years ago)

The Devonian strata over much of England and Wales, excluding the south-west peninsular, represent the first major group of nonmarine strata to be preserved in the geological succession. They have a characteristic purplish red-brown colour because of the iron oxide content, and are known as the Old Red Sandstone. At this time the British Isles lay at latitude 15º to 30º south of the Equator; the climate was tropical and semi-arid, but seasonally wet.

Traditionally the Devonian rocks have been divided into three parts, Lower, Middle and Upper. Lower and Upper Devonian rocks crop out over a large part of south Wales and the West Midlands and isolated inliers in the Bristol area, deposited within the Anglo-Welsh Basin, with a prominent unconformity present between the two successions. In south-west England Lower, Middle and Upper Devonian strata were deposited within a series of mainly marine basins. Isolated occurrences on Anglesey, the Lake District and the Cheviot Hills of Northumberland are associated with mainly Upper Devonian strata. Lower Devonian rocks are recognised in the subsurface in southern England below the Oxfordshire Coalfield (section 26) and undifferentiated Devonian strata occur at depth beneath the Kent Coalfield (section 27).

In south-west England (sections 12, 14), where Devonian sedimentation was more or less continuous, first in lacustrine basins and then in marine basins formed as narrow down-faulted graben along the northern reaches of an oceanic tract, the Rhenohercynian Ocean, that lay to the south of the uplifted Lower Palaeozoic landmass of southern Britain. The rift basins, which developed and filled sequentially from south to north, include the Gramscatho Basin, Looe Basin, South Devon Basin and the Tavy Basin. Only the lowermost part of the Lower Devonian strata is a nonmarine facies, deposited in a freshwater lake into which fluvial sediments were poured together with slumped debris. There is a transition into a fully marine facies, sandstone and mudstone of younger Lower, Middle and Upper Devonian strata. Depositional highs between the basins were generally maintained at shallow water depths and carbonate reefs developed, which were reworked from time to time so that limestone debris was eroded and deposited into the adjacent basins. Some of the major faults acted as conduits for magma with several tens of metres thick brecciated lavas, tuff and bedded volcaniclastic rocks preserved on some of the highs.

At Lizard Point and Start Point (section 12) a remnant of the Rhenohercynian ocean floor is preserved as a complex assemblage of ultramafic and mafic rocks, together with hornblende schist, gneiss and metamorphosed sediment and basalt. The rocks have been subjected to intense metamorphism, and were thrust into their present location in the late Devonian, during the closure of the Rhenohercynian ocean basin. This represented part of the Variscan deformation event that complexly deformed much of the Devonian and Carboniferous succession present within this region.

In the Anglo-Welsh Basin Lower Devonian strata are widespread and thick, exceeding 800 m (sections 8, 10, 12, 24, 25). Middle Devonian rocks are absent, and this appears to have been a time of erosion. Upper Devonian strata rest unconformably on the Lower Devonian, but are more restricted in outcrop, thinner, about 75 m, and are mainly fluvial cross-bedded sandstone deposits with some shallow marine sediments. In the West Midlands, the Lower Devonian rocks were largely removed by erosion prior to the deposition of younger strata, which may suggest greater uplift over the main part of the Midlands Platform. About 150 m of Upper Devonian strata, are preserved around Brown Clee Hill.

On Anglesey, the Old Red Sandstone facies is about 500 m thick, although the age of this succession is unknown. In the north-east of the Lake District, the Mell Fell Conglomerate is up to 3000m thick and ?mid to late Devonian in age. It forms small outliers resting unconformably upon Ordovician rocks. About 1000 m of mafic lavas and tuffs of Devonian age occur at crop in the Cheviot Hills. About 250 m thickness of Upper Devonian strata, mainly fluvial sandstones and conglomerates are also present in the subsurface, below Carboniferous strata, in the extreme north of Northumberland (section 32)

The final pulse of continental collision along the margin of gondwana (the Acadian Orogeny) is generally dated as early Devonian in age. During this event, the Lower Palaeozoic rocks across Wales and the Lake District were folded, faulted and weakly metamorphosed. Later orogenic plutons in the Lake District, such as the Shap and Skiddaw granites, are Early Devonian in age and postdate the Acadian deformation. The granite outcrops at the surface are only a small part of much larger concealed plutons (sections 3, 5). The Weardale granite, of Mid Devonian age, underlies the Alston Block (section 3, 4) is completely concealed beneath Carboniferous rocks.

Carboniferous rocks (359 to 299 million years ago)

Carboniferous rocks crop out southwards from the Scottish border through the Pennines and into the Midlands, in Wales, and in the south-west peninsula. Carboniferous rocks are also widely present in the subsurface, and are unconformably overlain by Permo-Triassic strata in eastern England and Kent.

In Britain the main divisions of the Carboniferous are Tournaisian, Visean, Namurian, Westphalian and Stephanian. These equate broadly with the older terms Carboniferous Limestone (Tournaisian/Visean), Millstone Grit (Namurian) and Coal Measures (Westphalian). Stephanian strata have only a restricted occurrence in England and Wales. Sedimentation began at different times on the various blocks and in the basins: for example in the Craven Basin, south Wales and Culm Basin, strata of Tournaisian age are exposed, but in Derbyshire and north Wales the oldest reliably dated strata are of early Visean age.

In early Carboniferous times the climate was hot, humid and wet, with a somewhat drier climate at the beginning and end of the period. The Variscan tectonic cycle began in late Devonian times, and was driven by the closure of the Rhenohercynian Ocean.

Late Devonian and early Carboniferous sedimentation patterns in northern and central England were controlled by structural blocks and basins, developed within a larger depositional basin known as the Pennine Basin. The blocks were characterised by relatively thin and incomplete sedimentary successions. The intervening basins include the Solway–Northumberland, Stainmore, Cleveland and Craven basins (where over 4000 m of strata are preserved). Local volcanism occurred during the early rifting phase of basin subsidence and lavas and tuffs were erupted both on land and on to the sea bed. Volcanic eruption and intrusions occurred intermittently throughout the Tournaisian and Visean. These igneous rocks are generally basaltic (mafic) in composition, and some of the intrusions are closely associated with the volcanic rocks.

The Southern Upland Massif formed the northern boundary of the Pennine Basin, the Wales–Brabant High separated it from a more marine-influenced basinal succession that covered the southern part of Britain, and where deposition was more or less continuous throughout the Devonian and early Carboniferous.

In northern England, sediments deposited by river systems form a major part of the earliest Carboniferous succession. This includes the Inverclyde Group of the northern flank of the Solway Basin–Northumberland Trough (sections 4, 36), up to 850 m thick, and the up to 300 m-thick Ravenstonedale Group of the Stainmore Trough and Askrigg Block (sections 3, 4). Sedimentation at the northern margin of the Pennine Basin continued from the Tournaisian into the Visean with accumulation of Border Group strata. The group is fairly thin at the northern margin of the basin but thickens southwards to more than 1300m in the centre of the Northumberland Trough (sections 4, 5, 36). Its lower part comprises repeated sequences of sandstone, mudstone and algal limestone. Higher in the group, the mudstone may be reddened locally and the sandstone is more variable and thin coals become fairly common. At the top of the group is a sequence, up to 500 m thick, that is dominated by thickly cross-bedded and coarse-grained, deltaic sandstone.

In central and parts of northern England and north and south Wales, the earliest Carboniferous succession is characterised limestone deposited on geographically isolated blocks (Carboniferous Limestone Supergroup). The carbonate accumulated in warm shallow shelf seas. These shallow-water platform carbonates form the Great Scar Limestone Group of the Yorkshire Dales and west Cumbria (sections 3, 4, 5). Basalts underlie the Great Scar Limestone north-west of the Lake District. The Great Scar Limestone Group is about 100m thick on the Alston Block, about 400m on the Askrigg Block, and nearly 800m in the Stainmore Trough. The Bowland High Limestone Group, of Tournaisian age, is present at crop in small inliers in north Lancashire, but is present extensively at depth (section 1, 5), with further platform carbonates present only in the subsurface in the southern Pennines. The Peak Limestone Group, which occurs at crop mainly in Derbyshire (section 6, 24, 34) comprises about 1000 m of limestones, with subordinate mafic extrusive and intrusive rocks. In north Wales, the Clwyd Limestone Group occurs at crop around Flint and the Vale of Clwyd (section 33), where it comprises about 750 m of limestone and in Anglesey (section 17) where a thin basal sandstone 60 m thick is overlain by about 650 m of platform carbonates.

In south Wales the shallow marine limestone succession includes the Avon Group, of Tournaisian age, in which bioclastic limestones are interleaved with dark mudstones, overlain by the limestone-dominated Pembroke Limestone Group, of late Tournaisian and Visean age. The succession in south Wales is present in Pembrokeshire (section 11) at least 1150 m thick, in Gower where it is about 1000 m thick, thinning dramatically northwards to about 100 m to the north of the South Wales Coalfield (section 25) and the Vale of Glamorgan (section 12, 24), where a comparable southward thickening into the Bristol Channel is observed. Equivalent platform carbonates are observed in the Forest of Dean, Bristol and Mendips areas (section 21) and in the subsurface beneath large parts of southern England (section 15, 27).

Within the Pennine Basin (section 1, 5), deeper water carbonates are interbedded with, forming the Craven Group. These range in age from Visean to Namurian and are up to 1150 m thick. In the Culm Basin of south-west England (section 12, 13, 22) carbonate turbidites of the Teign Valley Group were derived from the north and silicic turbidites from the south, present within a predominantly deep-marine mudstone- and radiolarian chert-dominated succession. Volcanic rocks of early Carboniferous age, the Tintagel Group, are common in the south-west, and were extruded along major rift faults.

Deltas built out across northern England as far south as the Askrigg Block during late Visean to Namurian time, recorded by deposition of the Yoredale Group. The Yoredale facies, typically comprises limestone, mudstone, sandstone, seatearth (palaeosol), ganister and coal, was deposited in low-lying alluvial and deltaic flats that were subject to regular marine incursion and accumulation of carbonate. The Yoredale Group is divided into three main formations on the relative proportions of the main lithologies, mudstone, sandstone and limestone. The Tyne Limestone Formation is restricted in extent to the Cheviot Block and Solway Basin–Northumberland Trough, thickening to a maximum of 900 m toward the axis of the basin (sections 4, 32, 36). The overlying Alston Formation, which includes thick bioclastic limestones, was deposited more extensively that the Tyne Limestone Formation, exposed extensively in the northern Pennines, Yorkshire Dales and north and east Cumbria (sections 1, 2, 3, 4, 5, 32, 36). The formation is generally thickest within the troughs, with up to 700 m present to the east of the Alston Block (section 36). The Stainmore Formation comprises a lower part with more equal proportions of mudstone, sandstone and limestone, with several chert horizons, and an upper sandstone-dominated succession lacking limestones. The formation has a comparable distribution to the underlying Alston Formation, with up to 600 m thickness to the east of the Alston Block (section 36).

The input of vast quantities of fluvial and deltaic sediments during the Namurian led to the progressive southward progradation of coarse siliciclastic deposits. In the central Pennine Basin, these fluvio-deltaic sandstones form the Millstone Grit Group. Marine incursions are represented by black mudstone. Non-marine mudstones are a significant component, with subordinate coal present locally, especially towards the top of the group. The group is most thickly developed at crop, up to 1400 m, in the Forest of Bowland and southern Pennines (sections 1, 4). The group extends southward to the Peak District, where the succession is about 400 m thick (section 34). The group is about 300 m thick in the Clwyd area of North Wales (section 33).

Facies equivalent to the Millstone Grit also occur to the south. The Namurian Marros Group of south Wales consists of locally derived quartzose sandstone, interbedded with non-marine mudstone and subordinate marine shales (sections 11, 12, 24, 25). The Holsworthy Group of south-west England was deposited as sandy turbidite lobes on a delta front within the Culm Basin. The group is up to 1300 m thick in north Devon (sections 12, 13) with thinner developments flanking the Dartmoor Granite (section 12, 14).

By Westphalian times, southern Britain had evolved into a landscape of rivers and lakes, lush equatorial forests and peat mires, and low-lying regions that were periodically inundated by the sea. Westphalian sediments consist of cycles of sandstone, siltstone and mudstone with subordinate seatearth, coal and ironstone. The mudstone is grey, characteristically carbonaceous and fissile. Marine mudstone bands have been important in correlation across the different Westphalian sedimentary basins and are used to define the formations of the Lower, Middle and Upper Coal Measures. The Pennine Coal Measures Group is present in the coalfields of central and northern England and north Wales. The main areas of crop are in west Cumbria and Canonbie (section 32), Northumberland and Durham (sections 3, 36), Lancashire (section 5, 18), Yorkshire–Nottinghamshire (sections 22, 34), South Staffordshire and Warwickshire coalfields (section 31, 6) and north Wales, extending below the Permo-Triassic rocks of the Cheshire Basin (section 33). A maximum thickness of about 1900 m is found in a mainly subsurface succession near Manchester, with the group thinning dramatically along the flanks of the Pennine Basin, i.e. west Cumbria, Northumberland, Durham, South Staffordshire, Warwickshire and north Wales. The Pennine Lower and Middle Coal Measures are most extensively developed, with the Pennine Upper Coal Measures Formation tending to be restricted towards the basin depocentre, i.e. Lancashire, Yorkshire–Nottinghamshire.

The South Wales Coal Measures Group occurs most extensively at crop across the Pembrokeshire (section 11) and south Wales (sections 10, 12, 24, 25) coalfields, with the thickest development about 900 m around Swansea. The group extends eastwards into the Bristol–Somerset area (section 21), where around 500m of strata are largely concealed beneath Mesozoic strata. The group is also proved in the subsurface in Berkshire (section 26) and Kent (section 27), with up to 285 m thickness proved in the latter coalfield. Volcanic and intrusive rocks are recorded within the Pennine and South Wales Coal Measures.

The youngest Carboniferous strata within the Pennine Basin are dominated by a red-bed facies, mainly mudstones, sandstones and locally conglomerates, of the Warwickshire Group that developed during late Westphalian to Stephanian times. The group is found particularly on the margins of the basin, for example in the West Midlands (sections 6, 18, 31) where the thickest development of 1225 m is present in the Warwickshire Coalfield, and in north Wales (section 33), and also in north and west Cumbria. The group is also present in the subsurface, beneath the unconformity at the base of Permo-Triassic strata in Lancashire (sections 18, 22), Nottinghamshire and Lincolnshire (section 34).

Deposition across much of south Wales and the southern part of England was fed by river systems that originated in the growing Variscan uplands to the south. These sandstone-dominated successions with thick coals form the plateau of the South Wales Coalfield (sections 10, 12, 24, 25), with up to 1500 m of strata. The succession also occurs also in the Forest of Dean and Bristol–Somerset coalfields (section 21) and in the concealed Oxfordshire (section 26) and Kent (section 27) coalfields. Calcrete palaeosols (caliche) are more abundant in the younger strata, an indication that the climate was drier during the late Westphalian and Stephanian.

Variscan deformation was instigated by continental collision in the late Devonian–early Carboniferous. By Visean times it had spread to north Cornwall and Devon (345 to 325Ma). At the end of the Variscan cycle, the supercontinent of Pangaea had been formed. Large-scale thrusting and overfolding in southern Britain marked the final phase of the Variscan Orogeny in latest Carboniferous and early Permian times. The Variscan Front Thrust, which represents the northern limit of pervasive Variscan deformation and metamorphism in southern England, occurs broadly along the southern flank of the Wales–Brabant High. A period of uplift and erosion resulted in the development of an extensive unconformity, with much of the Stephanian succession absent.

The culmination of the Variscan orogeny resulted in conspicuous intrusions of granites in Devon and Cornwall. The Bodmin and Dartmoor granites are part of a largely concealed batholith (section 14) that stretches some 250 km from the Isles of Scilly to near Exeter, and may be up to 20 km thick under Dartmoor. This major body was emplaced at the end of the Variscan orogeny, and dates from about 300 to 270 Ma (late Carboniferous to early Permian). In northern England intrusions at this time are dominated by the mafic Whin Sill Complex, of Stephanian age, which intruded mainly at the level of the Alston Formation (sections 3, 32, 36).

Permian (299-251 million years ago) and Triassic (251-200 million years ago)

The Permo-Triassic rocks cover a significant proportion of the surface area of England, forming a near continuous belt from Devon to the Midlands. From here, they extend up the eastern side of the country to Teesside, and the western side to north Lancashire and from Barrow in Furness around the Cumbrian coast to the Solway Firth and down the Eden Valley. The Triassic rocks form much the greater part, with sporadic small outcrops of Permian rocks in the south and a continuous narrow belt up the eastern side of the country from Nottingham to Teesside. Both occur extensively at subcrop over large areas of the country.

The Permian rocks are a varied sequence of rocks that range from continental mudstones, sandstones and conglomerates/breccias from the Midlands southwards, to a marine sequence in the east with common evaporate horizons in the north. Throughout the Permian and Triassic periods, the climate was very arid.

During the Triassic, post Variscan crustal extension gave rise to fault reactivation and subsidence of a number of discrete sedimentary basins: the Somerset-Wessex (e.g. section 21); Worcester (e.g. sections 17, 23); Knowle (e.g. section 31); Needwood (e.g. sections 6, 18), Stafford (e.g. sections 24, 31) and Cheshire basins (e.g. sections 18, 22, 33), where thick sequences of sediments accumulated. The Triassic rocks can be subdivided into three main groups. The oldest, the Sherwood Sandstone Group, is locally subdivided into three formations (e.g. sections 18, 22). The Sherwood Sandstone succession comprises mainly conglomerates and pebbly sandstones at the base, passing up into mainly sandstones with increasing thin beds of mudstone in the upper part. The group preserves deposition from a major river system that flowed northwards across much of England from Northern France. This unit, together with underlying aeolian sandstones of Permian age, forms one of the most significant aquifers in England.

Later in the Triassic, much of England became a peneplained desert surface. Unlike many modern deserts, sedimentation was dominated by fine grained ‘dust’. A high and saline water table formed an often damp ground surface that allowed the gradual accretion of the dust that formed the red mudstones and siltstones of the Mercia Mudstone Group. Periodic rain storms led to flash floods that deposited thin beds of green siltstone and sandstone. The saline ground water led to the common precipitation of gypsum close to the sediment surface. At times, this formed thick accumulations that have been worked in parts of the country. The sea was never very far away and subsidence in the major basins allowed inundation of marine waters at times that lead to the precipitation of locally thick units of halite. These are most numerous in the Cheshire Basin. The upper part of the Mercia Mudstone Group locally comprises green mudstones and siltstones of the Blue Anchor Formation that were deposited in brackish conditions.

At the end of the Triassic, there was a marine incursion that covered most of Britain, depositing mainly mudstones of the Penarth Group. This unit is not differentiated on the cross sections as it is thin. The topmost beds of Triassic age occur at the base of the Lias Group and, for convenience, are included with the Jurassic strata.

Jurassic rocks (200 to 145 million years ago)

The Jurassic outcrop curves southwards from the coast of Yorkshire to Dorset with an extension running westward through the Bristol Channel into south Wales. Outliers occur in the Cheshire Basin and north of the Lake District. The palaeogeographical landscape was inherited from the late Triassic main depositional centres in the Worcester, Wessex and Cleveland basins with the East England Shelf as a long-lived stable area stretching east towards the deep North Sea graben.

Transgression that had started during the late Triassic continued throughout the early Jurassic. The peneplained landscape was flooded as a result of a rise in sea level combined with a steady regional subsidence so that a warm shallow sea covered most of southern Britain, lapping against the landmasses, with coastal, lagoonal and estuarine sediments marking the imprecise boundary between land and sea.

The succession comprises a lower Lias Group of typically between around 250 and 500m in thickness and comprising grey mudstone with thin alternations of limestone common in the basal part, and sandstone and siltstone occur higher in the group (e.g. sections 12, 13, 23, 24) It reaches its greatest thickness in the Wessex-Weald Basin (sections 15, 26) but becomes thinner across the East Midlands Shelf, and pinches out south and east (sections 16, 29, 30, 31) against the London Platform. The group is also thickly developed in the Cleveland Basin (section 36). Away from the main outcrops the Lias Group is also present as outliers in the Cheshire Basin, and near Carlisle (section 32) where up to about 50 m of strata are present.

A major change that may be attributed to thermal doming in the North Sea occurred during mid Jurassic times, and there is evidence of volcanic activity in offshore areas. A widespread hiatus is recorded in the sedimentation pattern (Mid Cimmerian unconformity), particularly at the basin margins, and Middle Jurassic strata rest unconformably on Lower Jurassic or older strata indicating considerable erosion.

In southern England, open marine but generally shallow-water conditions prevailed, and ooidal and bioclastic limestones accumulated; these form the Inferior Oolite Group and Great Oolite Group. The Inferior Oolite reaches its thickest at depth below the Weald (sections, 7, 15, 26) and at outcrop in the Cotswolds where approximately 100m of strata are preserved. Thinner successions are preserved in Dorset and Somerset (10 to 30 m; sections 7, 13) and entire group is lost south-eastwards where the London Platform forms the eastern margin of the basin (section 26). Through the south Midlands the group is represented entirely by highly ferruginous strata, but northwards sandstone and ooidal limestone strata appear, leading to progressive thickening at outcrop and in the subcrop to 30 to 50 m (sections 31, 20, 34). Thickness and the ironstone- sandstone-limestone succession is maintained beyond the Humber and then the entire group is cut out at a structural high (section 4).

In Dorset the mudstone-dominated Great Oolite Group is between 200 and 300 m thick (section 13). Eastward at depth in the Weald it passes generally into limestone and is between 100 and 150 m thick (section 26) and a similar northward thickness change is seen through Somerset (section 15). The group continues northward and forms the dip slope of the Cotswolds (section 7) gradually thinning into the Midlands to 30 to 40 m (sections 16, 29), with incoming of sandstone at the base and other more subtle lithology changes. The Great Oolite persists eastwards at depth into East Anglia, thinning slightly before being cut out beneath the Cretaceous strata (section 31). North through Lincolnshire the group is about 20 to 30 m thick and limestone becomes subordinate. North of the Humber the strata are progressively overstepped by younger Jurassic and Cretaceous (section 4).

Further north, a series of substantial basin-bounding faults bring in the Middle to Upper Jurassic strata of the Cleveland Basin (section 36). The beds equivalent to the Inferior Oolite and Great Oolite groups were deposited in fluviodeltaic to nearshore conditions. Iron-rich sandstones are widespread at the base of the Middle Jurassic; termed the Dogger Formation, which at 1 to 12 m is generally too thin to represent on the cross sections, and is included with the overlying Ravenscar Group which comprises fluviodeltaic sandstone, siltstone and mudstone with some beds of coal and limestone. The group generally thickens eastwards across the basin, from under 150 m north of York to over 200 m at the coast, where it is very well exposed (section 2).

During the late Middle Jurassic, marine transgression brought about more uniform conditions across southern England. The succession is up to around 200m in thickness and comprises a lower sand division (Kellaways Formation, Osgodby Formation) and overlying mud-rich division deposited over all but the most northerly parts (Oxford Clay Formation; e.g. sections 2,15, 29, 36).

These are overlain by the Corallian Group which predominantly crops out in North Yorkshire (up to 140 m thick; section 36) and forms a succession dominated by sandstone and limestone. It can also be traced from the south Midlands (30 m thick; section 26) to Dorset (60 m thick; section 13), and in the subsurface through the Weald (up to 170 m thick; sections 15, 29). Where the Corallian Group is absent in the Midlands, these are grouped together with the West Walton Formation (sections 20, 31) together attaining 280 m in Lincolnshire.

The overlying Ampthill Clay and Kimmeridge Clay formations. These were deposited over a wide area of England in subsiding basins with deeper water conditions, and reaching 280 m thick in the Vale of Pickering (section 36), 60 m in Oxfordshire (section 26), almost 500 m in Dorset (section 13) and at depth in the Weald (sections 15, 36).

The youngest Jurassic beds are the Portland and Purbeck groups that are well exposed in the cliffs of the Isle of Portland. Outcrops of the Portland Group occur in south Dorset where the strata are 30 to 50 m thick (section 13) and in Oxfordshire where they are up to 13 m thick (section 35) and comprise sandstone overlain by limestone. The Jurassic–Cretaceous boundary is placed near the base of the overlying Purbeck Group.

Cretaceous Rocks (145 to 65 million years ago)

The breakup of the continent of Pangaea and the opening of the North Atlantic has dominated the tectonic history of the UK since Permian times. During this time extensional faults controlled the development of the Cretaceous sedimentary basins. Uplift and widespread erosion at the end of the Cretaceous Period, essentially representing an early phase of the Alpine Orogeny brought this cycle of basin development to a close.

During the Early Cretaceous deposition in a northern basin (Norfolk and Yorkshire and into the southern North Sea) was essentially marine. Within this region a structural high separated the Cleveland Basin (e.g. sections 4, 34) from a shallower East Midlands Shelf (e.g. sections 31, 35). In the Cleveland Basin, the lower unit comprises about 100 m of grey clay with sporadic calcareous and phosphatic nodules of the Speeton Clay Formation. This spans the Lower Cretaceous as the lateral equivalent of a thin succession on the East Midlands Shelf, and rests disconformably on the underlying Jurassic strata.

At this time in the Wessex Basin of southern England, two active depositional centres, most commonly called the Wealden Basin (e.g. sections 15, 27) and the Vectian (Channel) Basin (e.g. section 21), were separated by intra-basinal highs. In the Wessex Basin, the lower division, Purbeck Group records deposition in shallow marine, lagoonal environments and comprises 185m of interbedded mudstones, limestones and evaporates. The overlying Wealden Group, comprises around 700m of strata with a lower sandstone rich division and an upper mudstone division. Together, these are thought to have been deposited by braided rivers spreading sheets of sand on lagoonal mudflats.

Renewed marine transgression commenced during late Early Cretaceous times (early Aptian) with deposition of the Lower Greensand Group in southern England, comprising up to 240m of largely unconsolidated shoreface sands, and overlying Selborne Group, comprising an up to 110m succession of glauconitic sand passing laterally into mud recording deposition in deeper marine environments. Continued rise in sea level, effectively joining the northern and southern depositional areas as well as allowed overlap of the higher division onto older strata in Dorset and Devon. Strata of the Selborne Group in the northern basin comprise around 30m of locally red coloured, rubbly to massive chalk, limestone and calcareous mudstone.

The early Cretaceous depocentres of the Wessex Basin were separated by a structural high that is known to have been emergent during part of the early Aptian at least in the Southampton, Portsmouth and South Downs areas. In the subcrop, borehole evidence shows that there are no Lower Cretaceous sediments preserved over the high and that, to the north, the succession at outcrop in the Weald can be traced westward albeit at a considerably reduced thickness. South of the high, in the western outcrops of Dorset and Devon, correlation can be made with the successions on the Isle of Wight.

The overlying, Late Cretaceous Chalk Group spans both the northern and southern basins and is one of the nations' principal aquifers. It was deposited during continued marine rising sea level and comprises a pure, white limestone made up from the skeletal remains of tiny coccoliths and foraminifera, and coarser fragments of larger invertebrate animals. Intense bioturbation indicates that it formed as a sludge on the sea bed, which may have remained unlithified for some time. There was little input of terrigenous material; marl beds occur in the lower part of the Chalk Group but decrease significantly higher up. Nodular beds and 'hardgrounds' indicate some variation in the depositional conditions. Flint occurs as nodules and thin seams at certain horizons locally within the succession. The group has traditionally been subdivided into Lower, Middle and Upper Chalk and is shown with this basic subdivision on the majority of the sections although the Middle and Upper Chalk are grouped together as the White Chalk sub-group on the 1: 625 000 geological map, the Lower Chalk being represented as the Grey Chalk sub-group.

In recent years a more detailed lithostratigraphical subdivision of the Chalk into 7-8 formations has been proposed for the approximately 560m thick succession of southeastern England (e.g. sections 15, 29). This enhanced classification is shown on the cross-sections in areas where sufficient data exist to enable this refinement, included for example is the data from the Central London chalk model commissioned recently by the Agency. In this extended classification the Lower Chalk is subdivided into a lower West Melbury Marly Chalk and an upper Zigzag Chalk formations. The Middle Chalk is represented by the Holywell Chalk overlain by the New Pit Chalk and the Upper Chalk contains the Lewes Nodular Chalk (including the old 'Chalk Rock') overlain by the Seaford, Newhaven and Margate Chalk formations which are shown undifferentiated.

North of the Wash the sequence has an entirely different nomenclature and the following units can be distinguished in ascending order, the Hunstanton and Ferriby (undifferentiated), overlain by the Welton, Burnham and Flamborough Chalk formations totalling more than around 300m of strata (e.g. sections 4, 34).

Wolf Rock south-west of Land's End is an igneous intrusion (phonolite) of early Cretaceous age, and takes the form of a volcanic plug. Although the outcrop is unique in UK 'onshore' geology, igneous rocks, mainly basalt, are recorded offshore interleaved with early Cretaceous strata in the western English Channel.

Cenozoic Rocks (65 to 2.6 million years ago)

At the end of the Cretaceous Period uplift in southern Britain was associated with the onset of the Alpine Orogeny—the deformation episode driven by collision between the European and African plates. This Orogeny continued to influence deposition throughout the Palaeogene (65 Ma to 23 Ma) and Neogene (23 Ma to 2.6 Ma) with its maximum effect being felt within the late-early to middle Miocene (20 ma to 14 Ma) . The most obvious result was the creation of the mountain chains within southern Europe, but distant waves of this event were felt in Britain where uplift and eastwards tilting triggered erosion. However, the main Alpine structural effects had little impact beyond the developing depositional basins in southern England.

The most obvious effect is seen in the strata of the south of England, where there was inversion and uplift of the Cretaceous basins. Farther north, a very different Palaeogene history unfolded. Regional uplift and erosion preceding a major episode of magmatism spanned an interval from about 62Ma to about 55 Ma and largely predates the Cenozoic sediments (58 Ma to 28 Ma) that remain in the south of England. These volcanic and intrusive igneous rocks (the North Atlantic Igneous Province), emanated principally from central complexes in southern Scotland, but are only sparsely represented in England and Wales by the outer reaches of a dyke swarm and by numerous widespread ash beds recorded within the sediments in southern England. Many of the dykes (mainly of basalt and/or dolerite) that make up the regional swarms are less than a metre across, although dykes up to 10m across are fairly common.

Cenozoic deposition was largely concentrated in a shallow marine sedimentary basin, now preserved as two major synclinal structures in the south of England, the London and Hampshire basins (sections 28 and 26 respectively). During times of higher sea level there was intermittent connection with deeper grabens developing in the North Sea to the east and the Atlantic Ocean to the west. Apart from the widespread deposits of these basins, other, smaller outcrops occur in Devon near Bovey Tracey and Petrockstowe with smaller outcrops farther west in Cornwall. At Mochras on the west coast of Wales, there is a thick succession concealed beneath younger glacial deposits.

Elsewhere there are residual deposits of even younger Cenozoic sediments preserved in fissures and hollows in the underlying strata, and particularly in irregular karstic hollows developed on the top of the Chalk Group.

The Palaeogene and Neogene strata of southern England record alternating deposition on low-lying fluviatile braidplains with swamp and shallow lakes, to near-shore and deeper water marine. In the London Basin the succession comprises a lower Thanet Sand Formation, up to 30 m thick of pale yellowish grey sand that weathers to deep green the presence of glauconite. It has been burrowed extensively by marine creatures so that few bedding structures remain. This is overlain by the Lambeth Group, up to 20 m of interbedded sands, clays, pebble and shell beds deposited in shoreface to alluvial plain environments. The overlying Thames Group comprises around 150m of mostly marine clay with sand deposited in shallow marine or estuarine environments in the upper part.

In the Hampshire Basin, the Thanet Sand Formation is absent and the succession consists of the Lambeth, Thames, Bracklesham and Barton groups (Eocene), and the Solent Group (mainly Oligocene). The Bracklesham Group consists of around 140m of glauconitic sandy clay with many shells and some plant remains; the plant debris and roots indicate coastal marsh interfingering with the marine sediments. The Barton Group comprises up to around 140m of mainly clay in the lower part and sand in the upper part.

Oligocene beds occur in Hampshire and on the Isle of Wight as part of the Solent Group. This comprises up to around 200m of clay with units of limestone, ironstone and bituminous beds. Rich faunal remains include gastropods, fish, reptiles and various mammals. The beds were deposited in freshwater lakes, but there was also considerable brackish and marine influence.

In west Wales, the Mochras borehole penetrated 524 m of sand, silt, clay and lignite with conglomerates interbedded in the lower part. This thick sequence of river floodplain sediments is mainly Oligocene, and rests directly on the Lias Group of early Jurassic age.

In Devon at Bovey Tracey, a small but remarkably deep fault-controlled basin contains over 1000 m of Oligocene lacustrine sediment that includes kaolinite-rich clay derived from the weathering of granite, and lignite. Similar but thinner deposits occur at Petrockstowe.

A hiatus in sedimentation during Miocene times probably indicates the period of maximum uplift associated with the Alpine Orogeny. Late Miocene sand (Lenham Formation) occurs in east Kent at about 190 m above OD, and is possibly of marine origin.

In East Anglia, resting on an eroded surface of Cretaceous and Eocene strata, Pliocene sediments of the Crag Group (e.g. section 19) which l comprise up to 70 m of sand and gravel deposited in shallow marine conditions, but also include estuarine interbedded sand, silt and clay.

In Cornwall, well-stratified sands with clay and pebble beds are perched at elevations between 100 and 400 m above OD indicating substantial Neogene or post-Neogene uplift.

Quaternary superficial deposits (2.6 million years ago to present)

Most part the bedrock geology described above is concealed beneath a cover of loose detritus, soil and vegetation. Some of this has been formed in situ, from the weathering of the underlying rocks, but across much of the UK the superficial cover was introduced by ice sheets and meltwater during an ‘ice age’ that started about 2.6 million years ago and lasted until glaciers disappeared from the Scottish Highlands, only about 10,500 years ago.

During this period, bitterly cold intervals alternated with relatively warmer conditions, and the glaciers and ice sheets advanced and retreated accordingly. As they did so, they eroded upland areas, causing dramatic oversteepening and deepening of older river valleys and left behind deposits of till and glaciofluvial sand and gravel. Some of these deposits were sculpted by the passage of the ice into streamlined mounds and drumlin fields, the larger fields are clearly visible on satellite images, for example in northern Lancashire. Once the ice began to melt copious meltwater washed out vast spreads of sand and gravel while around the margins of the residual glaciers piles of debris built up creating distinctive landforms including moraine, eskers and kettleholes.

Final retreat of the glaciers during the Holocene saw establishment of the modern river drainage pattern across England and Wales with associated deposition of alluvium and river terrace deposits as well as accumulation of peat in areas of restricted drainage.

In the NGFD the thicker (>10m) superficial deposits are illustrated as impermeable – largely comprising till and glaciolacustrine deposits; permeable – largely glaciofluvial sand and gravel and modern alluvium; and mixed – reflecting heterogeneous successions.

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: http://geolib.bgs.ac.uk.

JACKSON, A. A. 2008. Bedrock Geology UK south. An explanation of the bedrock geology map of England and Wales -1:625 000 fifth edition. Keyworth, Nottingham: British Geological Survey

KESSLER, H., MATHERS, S. J. & SOBISCH, H.-G. 2009.The capture and dissemination of integrated 3D geospatial knowledge at the British Geological survey using GSI3D software and methodology. *Computers & Geosciences.* 35, 1311-21

LAWLEY, R. & GARCIA-BAJO, M. 2010. The National Superficial Deposit Thickness Model (version 5). *British Geological Survey Internal Report,* OR/09/049. 18pp.

SMITH, A. 2009. A new edition of the bedrock geology map of the United Kingdom. *Journal of Maps*, 232-252.

STONE P. 2008. *Bedrock Geology UK north. An explanation of the bedrock geology map of England and Wales -1:625 000 fifth edition.* Keyworth, Nottingham: British Geological Survey