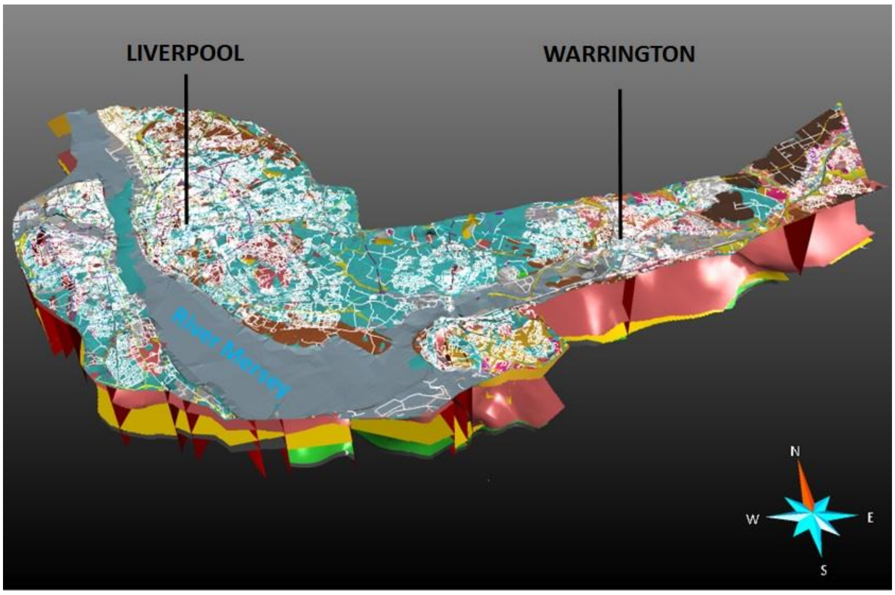
# 3D Geological Model Report for Liverpool, Warrington and Irlam Superficial and Bedrock model

National and International Geoscience Programme

Open Report OR/23/20



BRITISH GEOLOGICAL SURVEY

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# 3D Geological Model Report for Liverpool, Warrington and Irlam Superficial and Bedrock model

H Burke, R Terrington, S Thorpe, H Cullen-Gow, T Kearsey



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Keyworth, Nottingham British Geological Survey 2023

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# Foreword

This report is the published product of a study by the British Geological Survey (BGS). The report describes the data and methodologies for the construction of the Liverpool, Warrington and Irlam areas of the Lower Mersey Corridor, NW England.

# Acknowledgements

A large number of individuals in the BGS have contributed to the project. This assistance has been received at all stages of the study. In addition to the collection of data, many individuals have freely given their advice, and provided the local knowledge of the Lower Mersey Corridor. Of the many individuals who have contributed to the project we would particularly like to thank the following:

Simon Price

Gareth Jenkins

Dave Boon

Ian Cooke

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# Abbreviations

| | |
|---|---|
| BGS | British Geological Survey |
| BNG | British National Grid |
| DTM | Digital terrain model |
| ERT | Electrical resistivity tomography |
| GI | Ground investigation |
| LEX | BGS Lexicon of Named Rock Units (BGS's abbreviated codes for superficial and bedrock units) |
| Lidar | Light detection and ranging (lasers used to measure the elevation of features, typically used for digital terrain models) |
| mbgl | Metres below ground level |
| mOD | Metres above ordnance datum |
| OD | Ordnance datum |
| OS | Ordnance Survey |
| QA | Quality assurance |
| RCS | BGS Rock Classification Scheme (BGS scheme for classifying and naming geological materials) |
| UKRI | United Kingdom Research and Innovation (non-departmental public body of the Government of the United Kingdom) |

# 1 Introduction

This report describes the data and methodology used to construct the 3D geological model of the artificially modified ground, superficial deposits and bedrock of Liverpool, Warrington and Irlam, NW England (**Figure 1**). These areas form part of the Lower Mersey Corridor linking Liverpool to Manchester. Historically this been an important transport connection in this region between these cities along the Manchester Ship Canal and more recently by rail and road.

The 3D geological model was developed for the purpose of characterising lithological variability within superficial deposits and depth to rockhead. It is intended to be used for the assessment of engineering geological and geological ground conditions and their influence on aquifer vulnerability and recharge potential. The 3D geological model is not intended as a replacement for invasive ground investigation. It provides an additional tool for the development of a conceptual ground model in Liverpool, Warrington and Irlam.

The model was constructed to be compatible with, and equivalent to, a detailed 1:10 000 scale geological map. The model therefore includes geological units that would normally be resolved at 1:10 000 scale.

The total area of the BGS Liverpool, Warrington and Irlam 3D geological model is approximately 585 $km^2$ and ranges in elevation from 400 mOD to -300 mOD and is suitable for use at scales of 1:10 000 to 1:50 000.

The geological model includes the top, base and thickness for each natural and artificial superficial deposit within the area.

The BGS Liverpool, Warrington and Irlam 3D geological model report has been separated into the following sections:

- Bedrock and superficial geology (Sections 2, 3 and 4): provides the geological context of the Liverpool, Warrington and Irlam geological model areas
- Model datasets (Section 5): a description of the data used to inform the BGS Liverpool, Warrington and Irlam 3D geological model and the processes used on these datasets.
- Modelled surfaces and volumes (Section 6): a description of the surface horizons modelled for the BGS Liverpool, Warrington and Irlam 3D geological model.
- Superficial and bedrock geology modelling workflows (Section 7): the methodology used to model the superficial and bedrock geology in 3D
- 3D geological model quality assurance (QA), rules and assumptions and limitations (Sections 8, 9 and 10): a description of the 3D geological model QA procedures; the geological rules and assumptions that were applied to the 3D geological model, and the limitations around the use of the 3D geological model
- Uncertainty (Section 11): a qualitative assessment of the uncertainty is described.
- BGS Liverpool, Warrington and Irlam 3D geological model images (Section 12): 3D and cross-section images of the 3D geological outputs are provided for the horizons modelled.

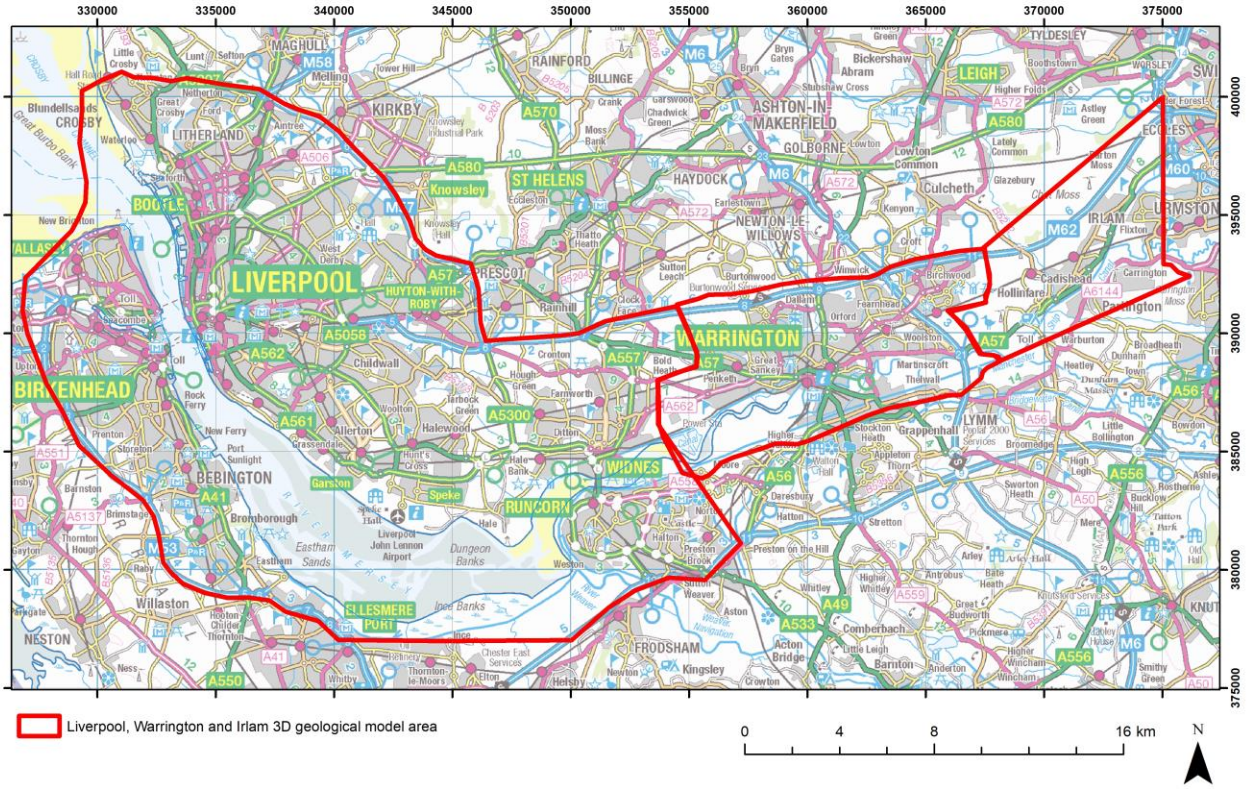


**Figure 1** Combined BGS Liverpool (west), Warrington (central) and Irlam (east) 3D geological model area. © Crown copyright and database rights 2023. OS AC0000824781 EUL

# 2 Bedrock geology

The BGS Liverpool, Warrington and Irlam 3D geological model area is underlain by formations within the Mercia Mudstone Group, the Sherwood Sandstone Group and underneath both, the Coal Measures Group (**Figure 2**).

The Sherwood Sandstone Group is the main bedrock unit that occurs at surface and under the superficial deposits. Lithologically, this is composed of sandstone, which is generally red, yellow and brown. It is part pebbly and conglomeratic in lower part. The pebbles are generally extraformational quartz and quartzite, with some intraformational clasts. Subordinate red mudstone and siltstone exists within the Sherwood Sandstone Group.

The Mercia Mudstone Group overlie the Sherwood Sandstone Group in the east of the model and comprises of mudstones and thin evaporate beds and sandstones. All are dominantly brown and red-brown in colour.

Below the Sherwood Sandstone Group, but above the Coal Measures Group is the Cumbrian Coastal group and Appleby Group. These are both thin in this area; the Cumbrian Coastal Group is on average 20 metres thick, and the Appleby Group is on average 100m thick. The Appleby Group is only found east of the western boundary fault although there is some uncertainty due the challenges identifying it in boreholes.

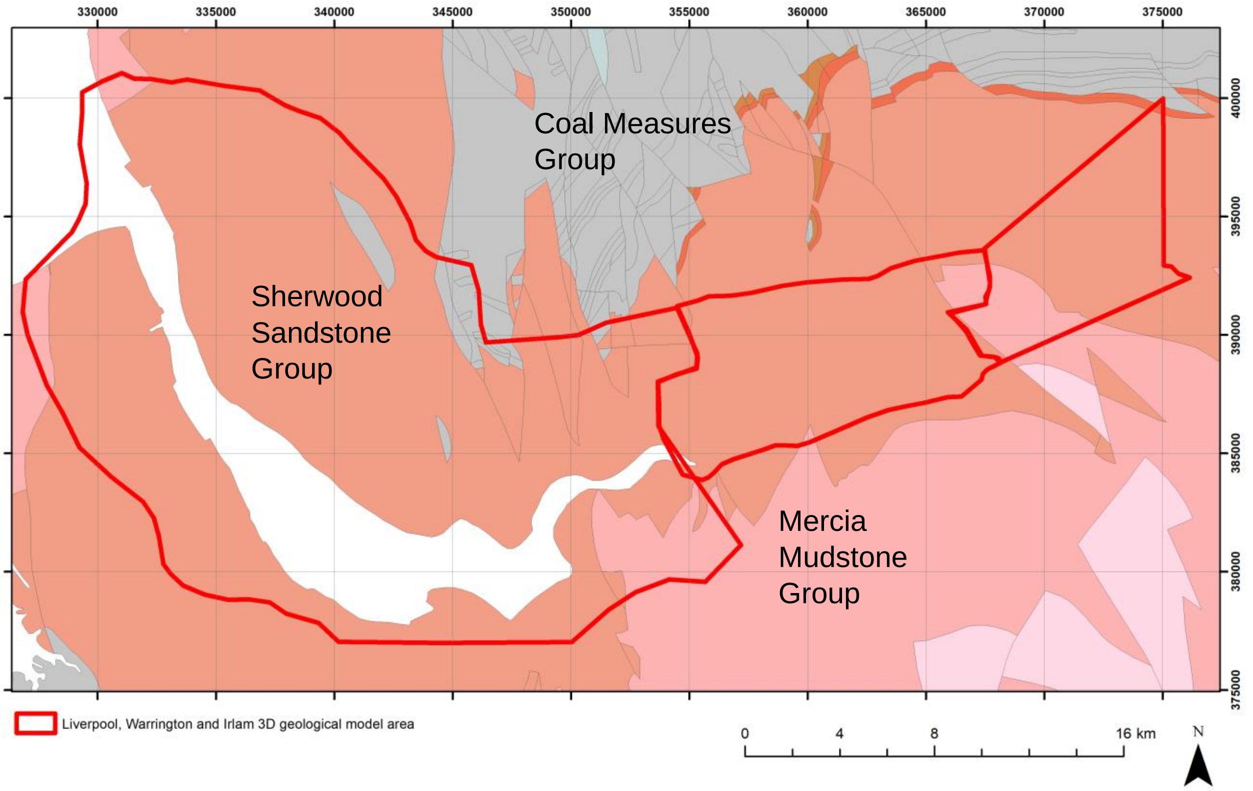


**Figure 2** BGS Geology 250k – 3D geological model area

# 3 Superficial geology

The present-day topography is largely the result of glacial processes that were active during the Pleistocene, but it has been modified by fluvial processes, mass movement and landslides. The Pleistocene deposits are a complex sequence of superficial deposits comprising glacial and post-glacial deposits, the main unit of which is Devensian Till (**Figure 3**). Lithological variability within the Devensian Till is high. Devensian Till is generally a poorly-sorted, unstratified mixture of rock fragments in a matrix of stiff, greyish-brown sandy clay. In many places many discrete lenses of glaciolacustrine silt and clay and glaciofluvial sand and gravel occur.

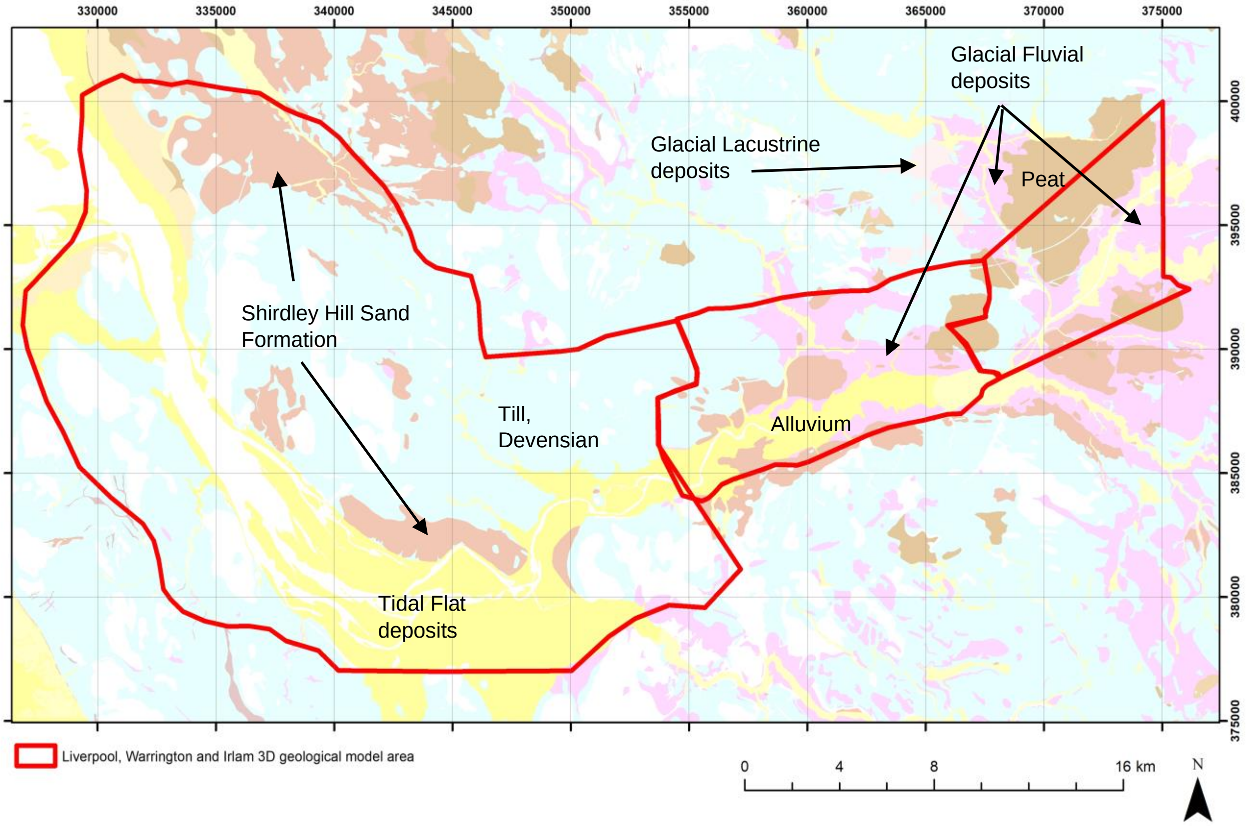


**Figure 3** BGS Superficial deposits 50k - 3D geological model area

# 4 Artificially Modified Ground

In the Liverpool, Warrington and Irlam areas, the Pleistocene and Holocene deposits are locally covered or altered by Artificially Modified Ground (AMG). AMG represents those areas where the ground surface has been significantly changed by human activity, usually divided into the following categories on BGS geological maps:

Made ground — areas where the natural land surface has been raised by the emplacement of human-made deposits, such as embankments and spoil heaps

Worked ground — areas where the ground has been cut away, such as quarries and road cuttings

Infilled ground — areas where the ground has been cut away, and then wholly or partially backfilled, such as an infilled pit or quarry

Landscaped ground — areas where the surface has been reshaped on a large scale, such as a golf course

Disturbed ground — areas of ill-defined shallow or near surface mineral workings where it is impracticable to map Made Ground and Worked Ground separately, such as areas of bell pit workings

Only prominent artificially modified ground features have traditionally been mapped on the BGS geology maps (e.g. quarries or rail and road embankments) and the more laterally persisting veneer of artificially modified ground has not been mapped in urban areas, such as shown on topographical maps. Further information on artificially modified ground mapping in BGS can be found on the BGS web site under BGS Geology themes: https://www.bgs.ac.uk/datasets/bgs-geology/bgs-geology-themes/#artificial

AMG is important but often under-represented in geological maps and models (Aldiss et al., 2014; Ford et al., 2014). It was not routinely mapped by the BGS until the 1980s, and modern AMG mapping has focused primarily on mineral workings, industrial areas and transport routes.

For the Liverpool-Warrington-Irlam model area AMG was inconsistently mapped, with partial coverage in Liverpool and Irlam and no coverage for the majority of the model area. To address this a detailed desk study was undertaken using historic Ordnance Survey maps, terrain models and borehole records to identify AMG and improve its representation in the 3D geological model. This study revealed hundreds of shallow pits, many of which are backfilled; the original, now infilled route of the River Irwell before it was canalised; and large spoil heaps where dredgings from the Manchester Ship Canal were deposited. As well as the classes of AMG described earlier in this section, the Manchester Ship Canal was captured as a separate worked ground unit. **Figure 4** (top) shows the original mapped distribution of AMG from BGS Geology 50K and the modelled extent following the desk study (bottom).

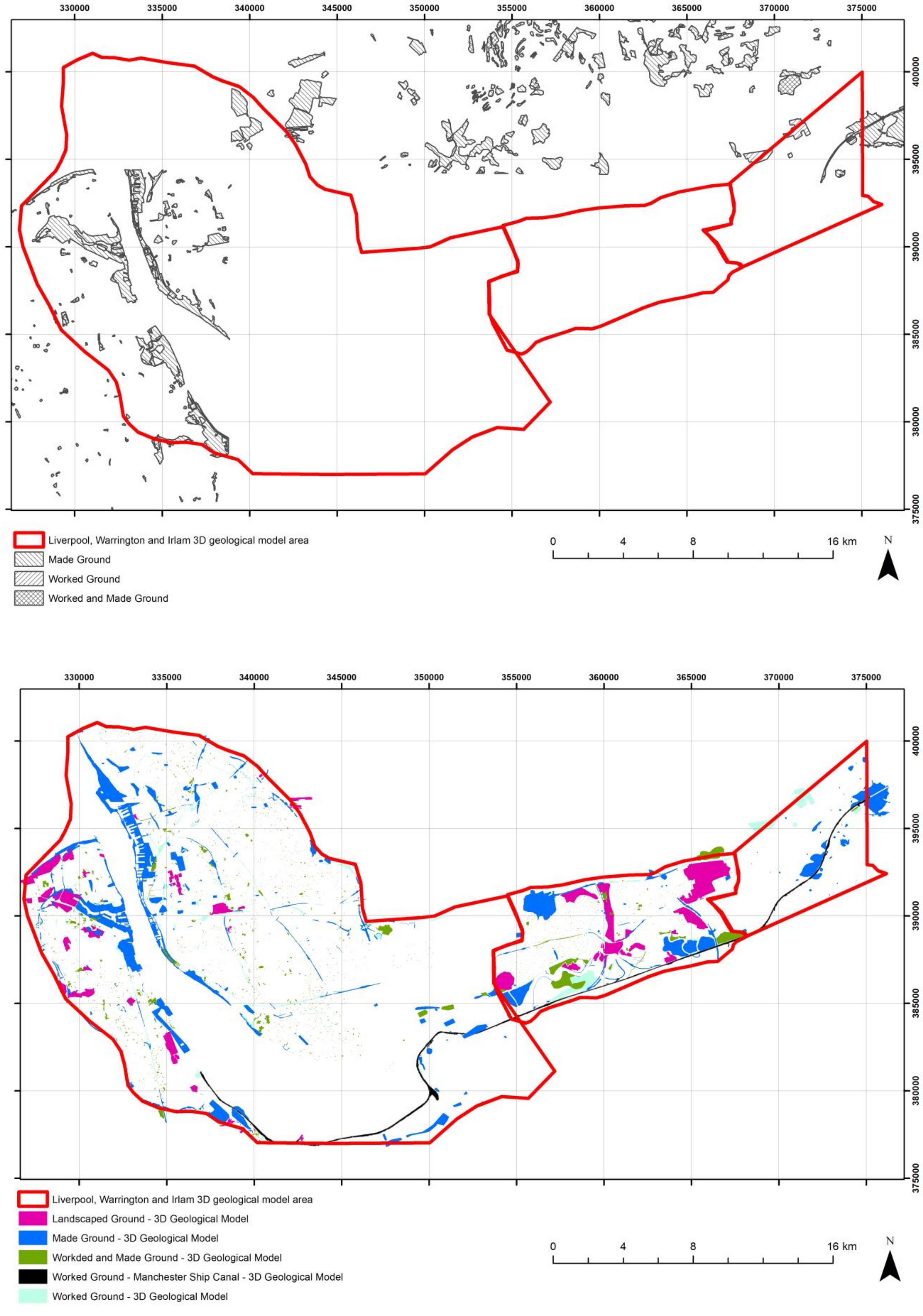


**Figure 4** Top: BGS Artificial Ground Geology 50k. Bottom: extent of AMG captured for the entire area in a detailed desk study

# 5 Model datasets

## 5.1 LIST OF DATASETS USED IN THE 3D MODEL

The following section describes the datasets used to inform the Liverpool-Warrington-Irlam 3D geological model.

- Digital terrain model:
    - OS Terrain 50 DTM (Ordnance Survey, 2023) https://www.ordnancesurvey.co.uk/products/os-terrain-50
- Bathymetry
    - United Kingdom Hydrographic Office (United Kingdom Hydrographic Office, 2023) https://www.admiralty.co.uk/access-data/seabed-mapping
- Borehole data:
    - Historical boreholes held by the BGS (Accessed via the BGS GeoIndex (British Geological Survey, 2022c) https://www.bgs.ac.uk/map-viewers/geoindex-onshore/
- Geological map linework:
    - BGS Geology 10K superficial geology map linework (British Geological Survey, 2012) https://www.bgs.ac.uk/datasets/bgs-geology-10k/
    - BGS Geology 50K superficial geology map linework (British Geological Survey, 2016a) https://www.bgs.ac.uk/datasets/bgs-geology-50k-digmapgb/
    - BGS Geology 50K Bedrock geology map linework (British Geological Survey, 2016b) https://www.bgs.ac.uk/datasets/bgs-geology-50k-digmapgb/
    - BGS Geology 50K linear features (British Geological Survey, 2016c) https://www.bgs.ac.uk/datasets/bgs-geology/bgs-geology-themes/#linear
    - Structural data - digitised
- BGS National Superficial Thickness Model (Lawley and Garcia-Bajo, 2009) https://www.bgs.ac.uk/datasets/superficial-thickness-model/
- Seismic interpretations (Andrews 2013)
- BGS historical 3D geological models:
    - Lower Mersey Corridor – Regional cross-sections – unpublished

## 5.2 DIGITAL TERRAIN MODEL

The Ordnance Survey Terrain 50 DTM was used as the land surface model cap. This was mosaicked with the bathymetry (see Section 5.3)

## 5.3 BATHYMETRY

Two surveys were downloaded from the United Kingdom Hydrographic Office:

- 2004 2006-361304 River Mersey New Brighton to Warrington
- 1998 2006-357964 River Mersey Crosby Channel to New Brighton

These were download as XYZ data and then calculated as a surface (**Figure 5**). The OS Terrain 50 DTM and bathymetry were mosaiced to give a combined coverage of elevation data (land surface and estuary bed surface). See **Figure 6** for the combined surface model.

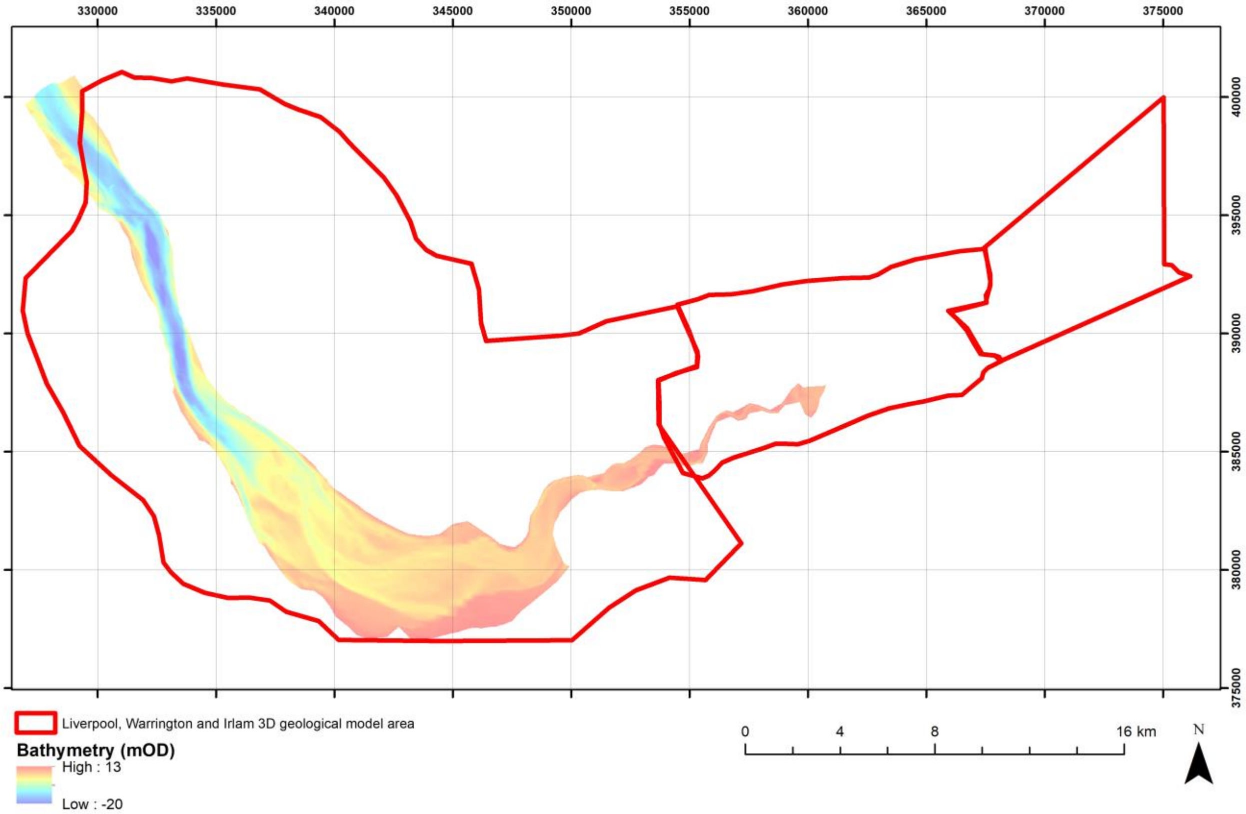


**Figure 5** Bathymetry - 3D geological model area. Contains United Kingdom Hydrographic Office Data © Crown copyright and database rights 2023

## 5.4 BOREHOLE DATA

Borehole data was extracted from the BGS borehole database and spatially analysed against those boreholes that had not been digitised into the BGS Borehole Geology database (log scans only). Where there were scanned borehole logs and not already digitised data, these were digitised into the Borehole Geology database.

Boreholes were digitised using the bedrock coding scheme using the BGS Lexicon of Name Rock Units (LEX (British Geological Survey, 2022a)) and the BGS Rock Classification Scheme (RCS) to log lithostratigraphy (British Geological Survey, 2022b) where possible. The unlithified coding scheme was used to record lithology (Cooper et al, 2006).

In total 2783 borehole were used to directly in cross-section interpretation for the 3D geological modelling of the superficial deposits (**Figure 6**), and a further 4505 boreholes were considered in the vicinity of the cross-sections and the 3D geological model project area.

The bedrock units are constrained by 282 boreholes (**Figure 7**).

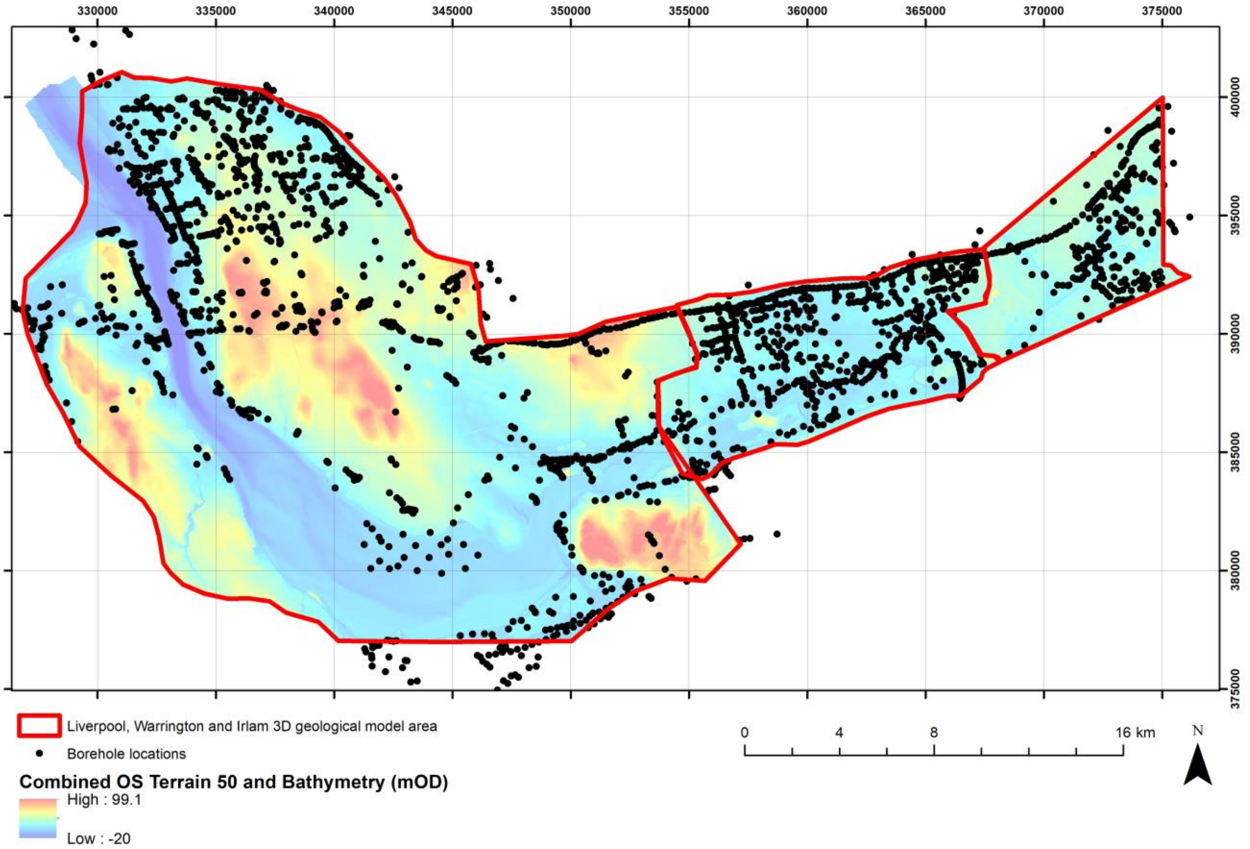


**Figure 6** DTM with bathymetry and locations of boreholes used to inform the Superficial 3D geological model. Contains OS data © Crown copyright and database rights 2023. Contains United Kingdom Hydrographic Office Data © Crown copyright and database rights 2023

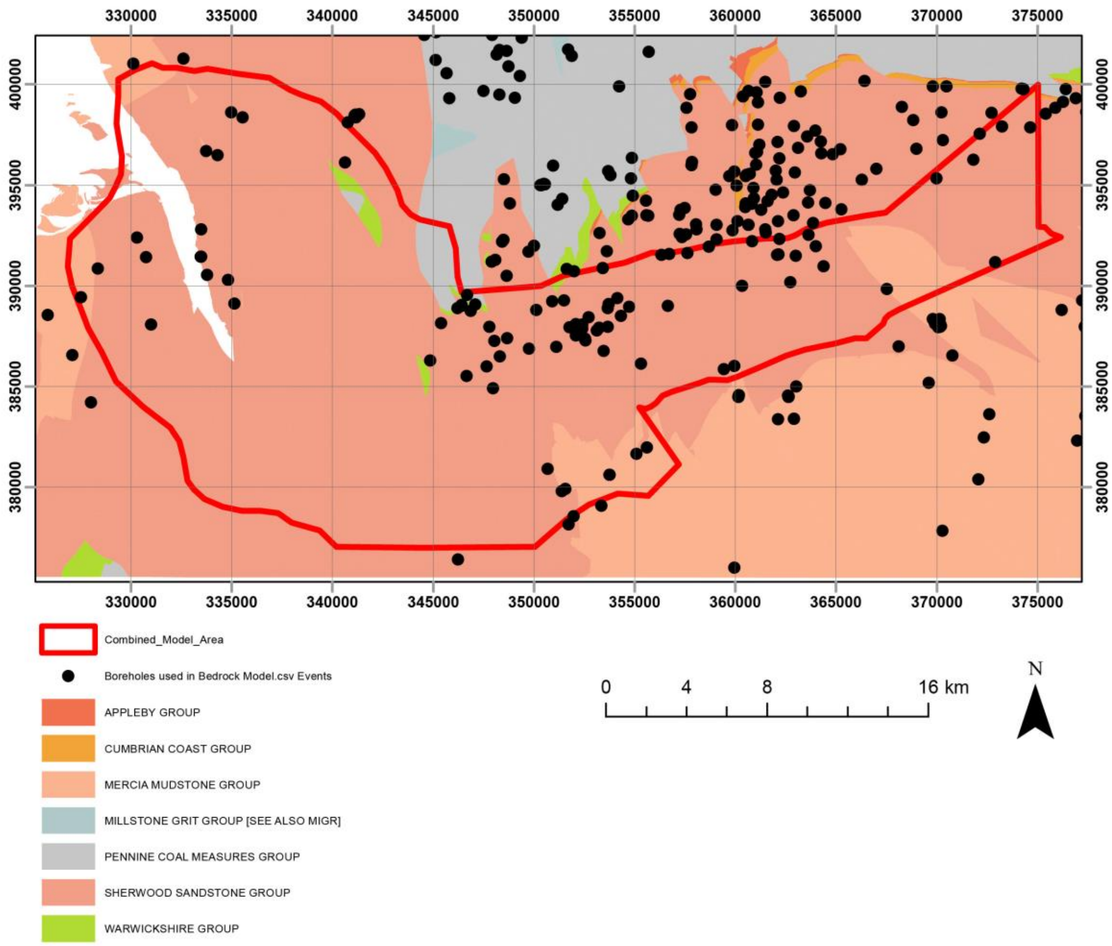


**Figure 7** Locations of the boreholes used to inform the bedrock model.

## 5.5 GEOLOGICAL MAP LINEWORK

The following geological map data were used to constrain the superficial and bedrock outcrops:

- BGS Geology 10K superficial geology map linework (British Geological Survey, 2012)
- BGS Geology 50K superficial geology map linework (British Geological Survey, 2016a)
- BGS Geology 50K Bedrock geology map linework (British Geological Survey, 2016b)
- BGS Geology 50K linear features (British Geological Survey, 2016c)

## 5.6 SEISMIC INTERPREATIONS

The lack of boreholes that penetrate deeper than the base of Sherwood Sandstone Group meant that there were issues controlling the bedrock model below that level. As a result, the depth converted seismic pick for the Variscan Unconformity (UVAR) from Andrews (2013) was used to help constraint the top of the Warwickshire Group in the model.

# 6 Modelled surfaces and volumes

**Table 1** below summarises the superficial deposits included in the Liverpool, Warrington and Irlam 3D geological model.

**Table 1** Liverpool, Warrington and Irlam 3D geological model units

| | Geological unit | Model unit | Lithology | Environment (inferred) | Model notation |
|---|---|---|---|---|---|
| Holocene | **Worked Ground** | Worked Ground | N/A | Anthropogenic<br>(Artificial ground) | wgr |
| | | Worked Ground (Manchester Ship Canal) | N/A | | wgr_cnl |
| | **Made Ground** | Made Ground | Mixed | | mgr |
| | **Landscaped Ground** | Landscaped Ground | Mixed | | lsgr |
| | **Worked and Made Ground (Infilled) Ground** | Worked and Made (Infilled) Ground | Mixed | | wmgr |
| | **Alluvium** | Overbank floodplain deposits | Silt, clay, | Fluvial | alv_1 |
| | | River channel deposits | Sand, gravel | (may include glaciofluvial element) | alv_2 |
| | **Tidal Flat Deposits (*note colour has modified for the 3D geological model to distinguish it from Alluvium)** | Estuarine alluvium where it overlies peat deposits | Clay, silt, sand, peat | Tidal flat | tfd_1 |
| | **Peat** (lowland bog) | Peat | Peat | Organic | peat_1 |
| | **Tidal Flat Deposits (*note colour has modified for the 3D geological model to distinguish it from Alluvium)** | Estuarine alluvium (including Downholland Silt) | Clay, silt, sand, peat | Tidal flat | tfd |
| | | Peat lens within tidal flat deposits | Peat | Organic | Peat_3 |
| Pleistocene (Devensian) | **Aeolian Deposits** | Shirdley Hill Sand Formation | Sand, peat | Aeolian | ssa |
| | **Glaciofluvial Deposits:** Sheet deposits (formerly Late Glacial Flood Gravels) | 1. Reworked sheet deposits in tidal reaches of the River Mersey<br>2. Sheet deposits<br>3. Glaciofluvial deposits | Sand, gravel<br>Sand, gravel<br>Sand, gravel, clay | High level terrace<br>Sub-till glaciofluvial deposits | gfsd_1<br>gfsd<br>gfdu_b |
| | **Ice-contact Deposits** | 1. Ice-marginal deposits<br>2. Intra-till channel deposits (major)<br>3. Intra-till lenses and sheet deposits (minor) | Sand, gravel, silt<br>Sand, gravel | Moraine?<br>Sub/supra glacial drainage<br>Sub/supra/en-glacial drainage | gfic<br>gfdu_1<br>gfic_l3_t to gfic_l10_t, gfic_b |
| | **Glaciolacustrine Deposits** | 1 Ice-marginal deposits<br>2. Sub-till deposits (restricted distribution) | Laminated silt and clay | Ice-marginal<br>Ice-proximal | glld_1<br>glld_2 |
| | **Till** | Till | Till, interbedded sands, impersistent laminated clays | Lodgement and melt-out tills, undivided | till_1, |

| | Geological unit | Model unit | Lithology | Environment (inferred) | Model notation |
|---|---|---|---|---|---|
| Triassic | **Mercia Mudstone Group** | MERCIA MUDSTONE GROUP | Dominantly red, less commonly green-grey, mudstones and subordinate siltstones with thick halite-bearing units in some basinal areas. Thin beds of gypsum/anhydrite are widespread; thin sandstones are also present. | | |
| | **Sherwood Sandstone Group** | SHERWOOD SANDSTONE GROUP | Sandstone, pebbly; conglomeratic in lower part;; subordinate red mudstone and siltstone. | | |
| Permian | **Cumbrian Coast Group** | CUMBRIAN COAST GROUP (COLLYHURST SANDSTONE FORMATION) | Red sandstones | Aeolian dunes | |
| | **Appleby Group** | APPLEBY GROUP (MANCHESTER MARLS FORMATION) | Red calcareous mudstone and siltstone with thin beds of fossiliferous marine limestone and dolomite | | |
| Carboniferous | **Warwickshire Group** | WARWICKSHIRE GROUP (ETRURIA FORMATION) | Mottled mudstone, with lenticular sandstones and conglomerates referred to as 'espleys'. | | |
| | **Pennine Coal Measures Group** | PENNINE COAL MEASURES GROUP | Interbedded grey mudstone, siltstone and pale grey sandstone, commonly with mudstones containing marine fossils in the lower part, and more numerous and thicker coal seams in the upper part. | Deltaic | |
| | **Millstone Grit Group** | MILLSTONE GRIT GROUP | Interbedded sandstones, grey mudstone, siltstone | Deltaic | |

# 7 Model workflow

## 7.1 SOFTWARE VERSIONS

The BGS Liverpool, Warrington and Irlam 3D geological model was constructed in two parts.

The superficial deposits were modelled using of GSI3D (v2013) software for the AMG and superficial deposits. The Bedrock was model was built using SKUA GOCAD (v22) and the faults were constructed first using LOOP3D (Grose et al 2021, Jessell et al. 2021)

Sections 7.2 and 7.3 describe the workflow applied to the BGS Liverpool, Warrington and Irlam 3D geological modelling of the superficial deposits and bedrock.

## 7.2 ARTIFICIALLY MODIFIED GROUND AND SUPERFICIAL DEPOSITS 3D GEOLOGICAL MODELLING WORKFLOW

The standard GSI3D modelling workflow was followed for the superficial deposits. GSI3D software utilises a range of data such as boreholes, DTMs and geological linework to enable the geologist to construct a series of interlocking cross-sections. Borehole data is represented in GSI3D by two proprietary files: a borehole identification file (.bid), that contains ‘index’-level information including location and start-heights; a borehole log file (.blg), that contains the borehole interpretation. Constructing cross-sections is intuitive and flexible, combining borehole data whereby bases and minimum depths are identified and digitised between considering outcrop data with the geologist's experience to refine the interpretation. Explanations for base depth and minimum depths are provided below:

The base of a stratigraphical unit was proven where the geological unit sits on another geological unit in the borehole, e.g. Alluvium on River Terrace Deposits.

The minimum depth of a geological unit is determined where the base of a stratigraphical unit was not proven (i.e. the borehole 'spuds out' within that subunit). For example the borehole terminated within the unit, rather than reaching the base of the unit. These are referred to as minimum depth markers and show the minimum depth to the base of a unit. The minimum depth markers were used to ensure the base of a particular horizon went below the marker in the 3D geological model.

Using both the information from the cross-sections and the distribution of each unit a calculation algorithm creates the triangulated surfaces for the top and base of each unit. To control the relative vertical ordering of the calculation, a generalised vertical section file (.gvs) is established (Section 6). A legend file (.gleg) is created to control symbolisation of the cross-section and model. The modeller can view all the units in 3D and iteratively return to the cross-section to make amendments or add further cross-sections to refine the model. This process is a standard methodology within BGS for modelling Quaternary and simple bedrock horizons and is fully documented in Kessler et al (2009).

Artificially Modified Ground (AMG) was modelled according to a semi-automated methodology defined during the modelling. The methodology produced scattered data point files (XYZs) for areas defining the Artificially Modified Ground classes. Made Ground (mgr) and Landscaped Ground (lsgr), and all instances of artificial material (made ground including engineered fill) proved in borehole and trial pit records and digitised in the project database were selected. Boreholes that had AMG recorded, but not included along cross-section interpretation but within the project area were also selected. The thickness was calculated using the start elevation of the record (in mOD) where it was present. In all other instances, the start elevation was derived from the OS Terrain 50 DTM elevation data.

For Worked Ground (wgr) and Worked and Made Ground (wmgr, also known as infilled ground), the depth of excavation was taken to be 0.2 m and 2.9 m below ground level respectively. This depth was selected to provide consistent visualisation of worked and worked and made ground as it was beyond the scope of modelling activity to identify individual records of depth of excavation for each instance of worked ground. The Manchester Ship Canal (whr_cnl) was modelled to its excavation depth of 8.5 m.

## 7.3 BEDROCK 3D GEOLOGICAL MODELLING WORKFLOW

The bedrock model was capped by a rockhead surface generated from the superficial model and was constructed in two parts. First the 1:50 000 bedrock map outcrop and fault data (British Geological Survey, 2016b, 2016c), along with the dip and strike data from the published map were run through the Map2Loop application (Jessell et al. 2021). This was used to calculate the thickness of the units and the throw of fault. Faults less than 5 km were removed. These results from Map2Loop were then passed to LOOP Structural to calculate a draft of the 3D geological model of the bedrock. Due to the high variation in the thicknesses (**Error! Reference source not found.**) and a number of unconformities of the units it was not possible to model the strata in LOOP Structural.

All the data described above was imported in to the SKUA-GOCAD modelling software, and using the Structure & Stratigraphy implicit workflow a model was calculated. All faults were assumed to have to be vertical, although SKUA-GCOAD did adjust these based on information from borehole data. Many of the stratigraphic boundaries in the BGS Borehole Geology database were revised using re-interpretations as a result of this modelling process. The final borehole stratigraphic interpretations are shown in Appendix 1. Many of the boundaries between units are unconformities. **Figure 8** shows the nature of the unconformities used in the final model.

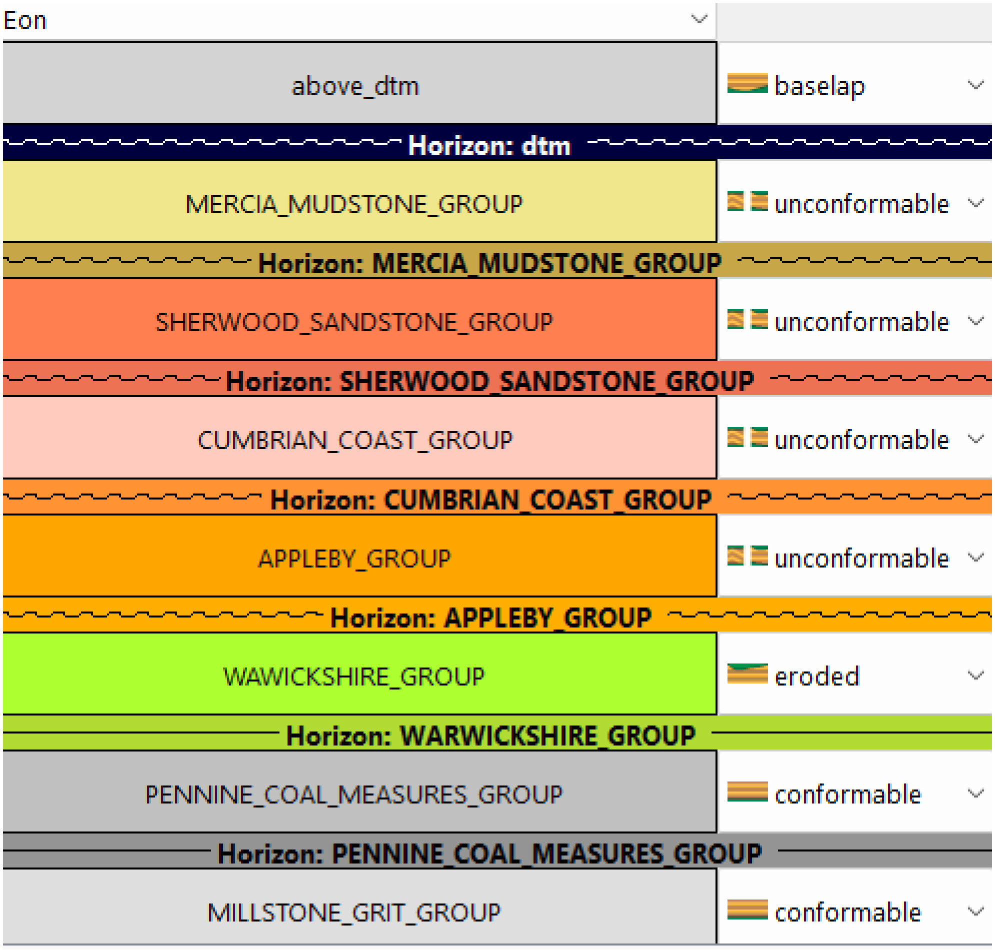


**Figure 8** Stratigraphy and unconformities used in the SKUA-GOCAD Bedrock model.

SKUA-GOCAD created a volumetric grid with a horizontal cell size of 500m and 10 cell in the vertical plane which vary depending on the thickness of the unit (c.f. Newell 2018a). These were the default values suggested by modelling workflow in SKUA-GOCAD because of the depth and lateral extent of the model. The bedrock model was constructed down to -1000 mOD to calculate the structural deformation in the Carboniferous. However, the final model cut-off depth is -300 mOD because below this depth the model uncertainty increased rapidly.

# 8 Model assumptions and geological rules

The interpolated structural data is representative of the geology at the scale of the model.

The bedrock model was limited to Group level, and it was not possible to resolve the formational variation in this project (Newell 2018b).

During 3D geological modelling, historical boreholes held by the BGS were re-interpreted in context with other evidence when visualising them together in cross-section and in 3D.

All sand and gravel deposits where they were proved in within the main till were assigned to individual lenses and interpreted as ice-contact deposits.

AMG was modelled according to a semi-automated methodology defined during the process of 3D geological modelling. Assumptions were made on thickness based on the averages and median values obtained from the borehole records.

# 9 Model limitations

## 9.1 USER GUIDANCE FOR THE BGS LIVERPOOL, WARRINGTON AND IRLAM 3D GEOLOGICAL MODEL

Users should note that a 3D geological model is a generalisation of reality and the full complexity of the geology may not be represented. The model is constrained by the data available at the time of construction; other interpretations may be valid. The extents of geological units shown on the approved geology maps (GeologyGB) may have been modified in the modelling process using evidence such as borehole logs that may not have been available at the time of survey. Users of the 3D geological model outputs use it at their own risk.

**The 3D geological model is an interpretation only and actual ground conditions encountered may be different from those shown in the BGS Liverpool, Warrington and Irlam 3D geological model.**

## 9.2 MODEL SPECIFIC LIMITATIONS

A 50 m cell size DTM (OS Terrain 50) was used to provide consistent model calculation across the Lower Mersey Corridor area including Liverpool, Warrington and Irlam. The DTM resolution may not resolve detailed landforms of Quaternary significance within urban areas.

The following thicknesses were applied to the AMG classes using a combination of median and average thickness values taken from the interpreted borehole data.

Made Ground (mgr) = 2.2 m

Landscaped Ground (lsgr) = 1.5 m

Worked and Made Ground (wmgr) = 2.9 m

Worked Ground (wgr) = 0.2 m (this was to show ground disturbance in the 3D geological model)

These depths were selected to provide consistent visualisation of worked, and worked and made ground as it was beyond the scope of modelling activity to identify individual records of depth of excavation for each instance of worked ground.

A number of different non-matching sources have been used to capture artificial units. This has resulted in duplication of mgr with wmgr areas. There are several areas where artificial ground is no longer present or relevant to the current land surface and the Digital Terrain Model (DTM). For example, some artificial ground areas are derived from historical maps, and more recent activity in these areas will have obliterated the original units and replaced them with other artificial ground types.

Natural superficial deposits can appear over-thickened where the DTM picks out artefacts such as bridges. Traditionally artificial ground is not mapped through the spans of bridges because the land level remains unchanged and artificial ground is only present in the bridge footings. However, the DTM uses the elevation of the bridge rather than the natural land surface beneath.

Some boreholes take their ground surface elevation values (start heights) from the tops of soil heaps, sometimes around 10m above the natural ground level/base of artificial ground. Initially the borehole start heights were honoured, with no artificial ground modelled in these areas. Made ground was later added to accommodate the spoil heaps, and the bases of natural superficial deposits were lowered to maintain their original thicknesses.

## 9.3 GENERAL MODELLING LIMITATIONS

The following is a list of BGS approved generic limitations that may apply:

Note: Not all of these statements will be applicable due to the modelling approach used and the type of geology modelled, please remove any that do not apply to your particular model. Also, this list is not exhaustive, and geologists/modellers are required to record any localised geological or technical limitations of the geological model in question.

- Geological interpretations are made according to the prevailing understanding of the geology at the time. The quality of such interpretations may be affected by the availability of new data, by subsequent advances in geological knowledge, improved methods of interpretation, improved databases and modelling software, and better access to sampling locations. Therefore, geological modelling is an empirical approach.

- The geological map linework in the model files may be modified during the modelling process to remove detail or modify the interpretation where new data is available. Hence, in some cases, faults or geological units that are shown in the BGS approved digital geological map data (GeologyGB) may not appear in the geological model or vice versa. Modelled units may be coloured differently to the equivalent units in the published geological maps.

- Best endeavours (detailed quality checking procedures) are employed to minimise data entry errors but given the diversity and volume of data used, it is anticipated that occasional erroneous entries will still be present (e.g. borehole locations, elevations etc.). Any raw data considered when building geological models may have been transcribed from analogue to digital format. Such processes are subjected to quality control to ensure reliability; however undetected errors may exist. Borehole locations are obtained from borehole records or site plans.

- Digital Terrain Models (DTMs) are sourced externally by BGS and are used to cap geological models. DTMs may have been processed to remove surface features including vegetation and buildings. However, some surface features or artefacts may remain, particularly those associated with hillside forests. The digital terrain model may be subsampled to reduce its resolution and file size; therefore, some topographical detail may be lost.

- Geological units of any formal rank may be modelled. Lithostratigraphical (sedimentary/metasedimentary) units are typically modelled at Group, Formation or Member level, but Supergroup, Subgroup or Bed may be used. Where appropriate, generic (e.g. alluvium – ALV), composite (e.g. West Walton Formation and Ampthill Clay Formation, undifferentiated – WWAC) or exceptionally informal units may also be used in the model, for example where no equivalent is shown on the surface geological map. Formal lithodemic igneous units may be named Intrusions or Dykes or may take the name of their parent (Pluton or Swarm/Centre or Cluster/Subsuite/Suite), or if mixed units Complex may be used. Highly deformed terranes may use a combined scheme with additional rank terms. Artificially Modified Ground units (e.g. Made Ground (undivided) – MGR, Landscaped Ground (undivided) – LSGR) are currently regarded as informal.

- Borehole coding (including observations and interpretations) was captured in a corporate database before the commencement of modelling and any lithostratigraphic interpretations may have been re-interpreted in the context of other evidence during cross-section drawing and modelling, resulting in a mismatch between BGS databases and modelled interpretations.

# 10 Model quality assurance

For a geological model to be approved for publication or delivery to a client, a series of quality assurance (QA) checks is carried out. This includes:

- an inspection of the input data
- the modelling methods used
- the associated model metadata report
- visual examination of the model outputs and modelled geological surfaces, which are checked for artefacts such as spikes and thickness anomalies

The naming convention of the modelled geological units is checked to ensure that recognised entries in the BGS Lexicon of Named Rock Units (British Geological Survey 2020a) and the BGS Rock Classification Scheme (British Geological Survey, 2020b). Further details of this procedure can be found in Gow et al. (2013).

# 11 Model uncertainty

There has been no attempt to establish quantitative model uncertainty up to the time the model and metadata report were published. However, qualitatively, it is evident that there is plenty of scope for uncertainty in the model to arise.

In general as the depth of the model increases, the accuracy of the projected surfaces decreases because most boreholes terminate in the top 20 m or so. This makes predicting the strata at depth particularly difficult. Experiences of 3D geological modelling in the Palaeozoic elsewhere in the UK (Burkin and Kearsey, 2019) has shown that the variation in thickness is a good proxy for the maximum error on any surface (**Table 2**). Therefore, it appears likely that the maximum error on the surfaces is of that order but will vary with the terrain and how active any faults were during deposition.

**Table 2** Variation in the thickness of bedrock unit observed in boreholes. Note that some units vary by as much as 500m in thickness.

| Stratigraphic Unit | Number Of Boreholes that intersect unit | Min thickness of unit (m) | Max thickness of unit (m) |
|---|---|---|---|
| Mercia Mudstone Group | 8 | total thickness not proven | total thickness not proven |
| Sherwood Sandstone Group | 43 | 447 | 1125 |
| Cumbrian Coast Group | 27 | 14 | 410 |
| Appleby Group | 26 | 15 | 193 |
| Warwickshire Group | 35 | 16 | 334 |
| Pennine Coal Measures Group | 6 | 163 | 547 |

The bedrock model tried to match the borehole data as best it can. In most cases it managed to do this at the scale of the model. However, for the Mercia Mudstone, Appleby and Warwickshire groups it reported an average vertical error of ~10 m.

# 12 Three-dimensional model images

Figures 9 to 12 are 3D views of the model. **Figure 9** shows the full extent of the model with all units shown. **Figures 10**, **11** and **12** focus on the Liverpool, Warrington and Irlam areas.

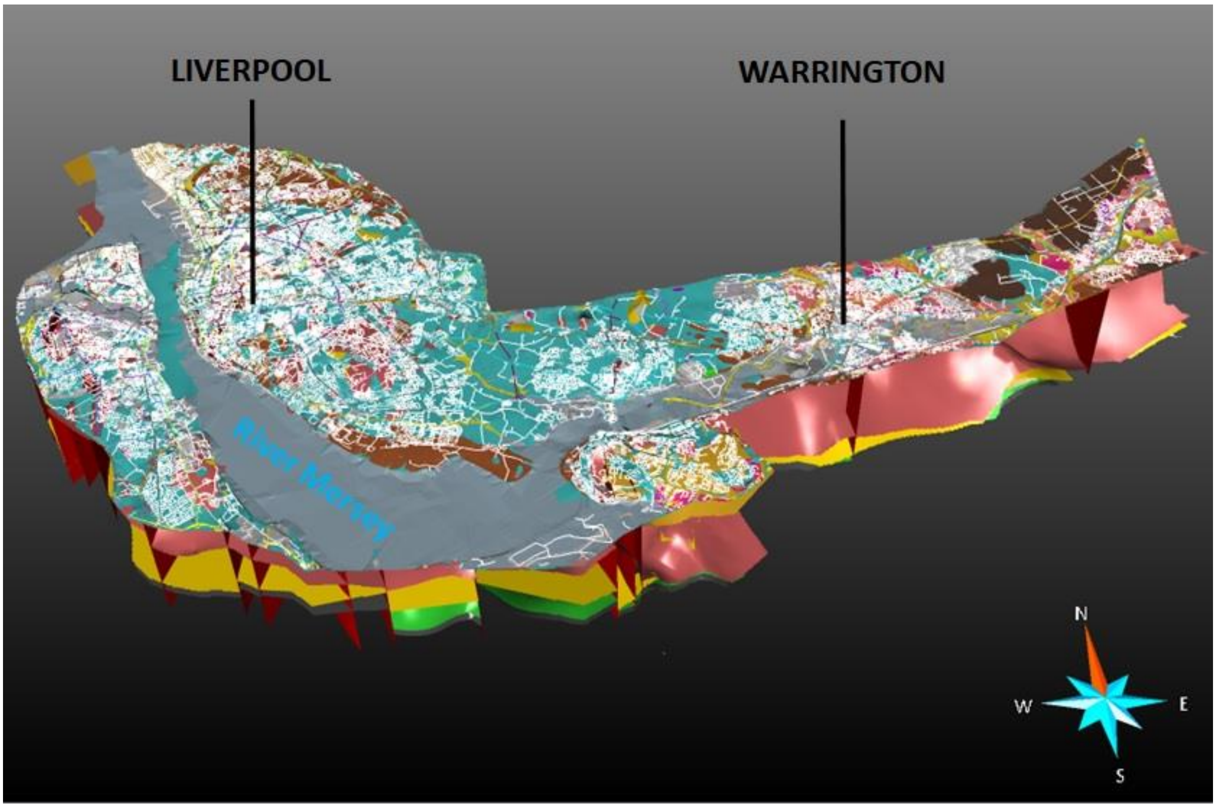


**Figure 9** 3D view of the combined superficial and bedrock model with 10x vertical exaggeration. Legend as per Table 1

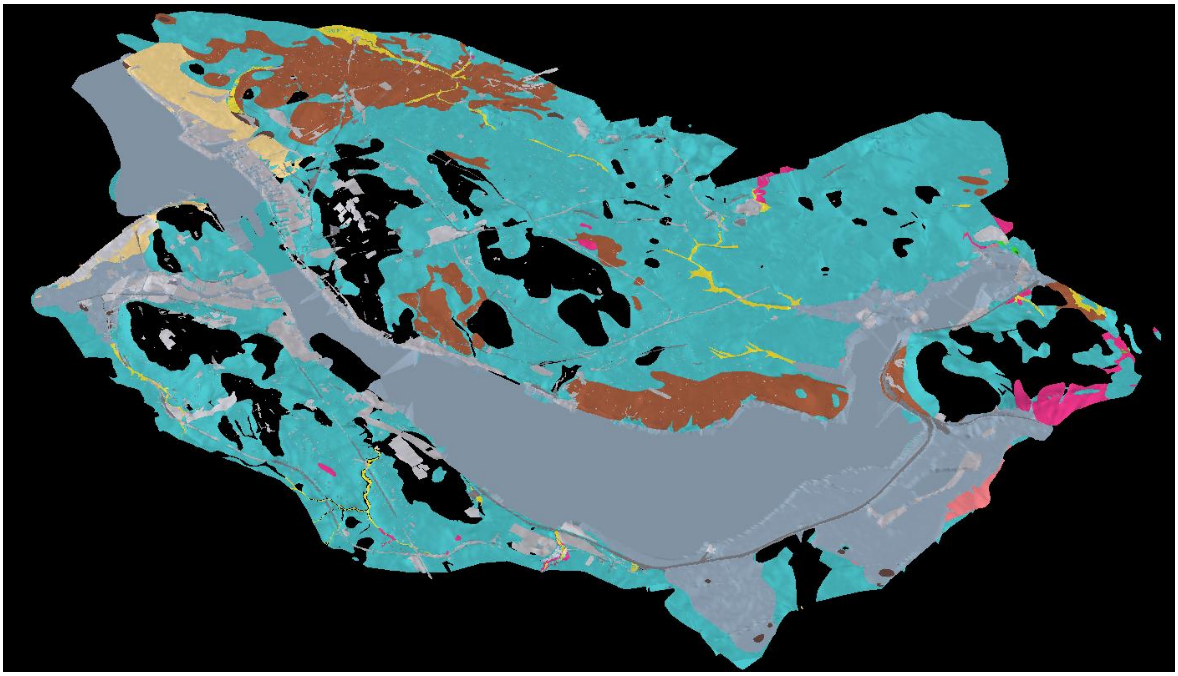

**Figure 10** 3D view of the superficial deposits and artificially modified ground in the Liverpool area, looking from the south, vertical exaggeration x10. Black areas indicate areas of bedrock at surface. Legend as per Table 1.


**Figure 11** 3D view of the superficial deposits and artificially modified ground in the Warrington area, vertical exaggeration x10. Legend as per Table 1. Contains Ordnance Survey data © Crown copyright and database rights 2023. OS AC0000824781 EUL

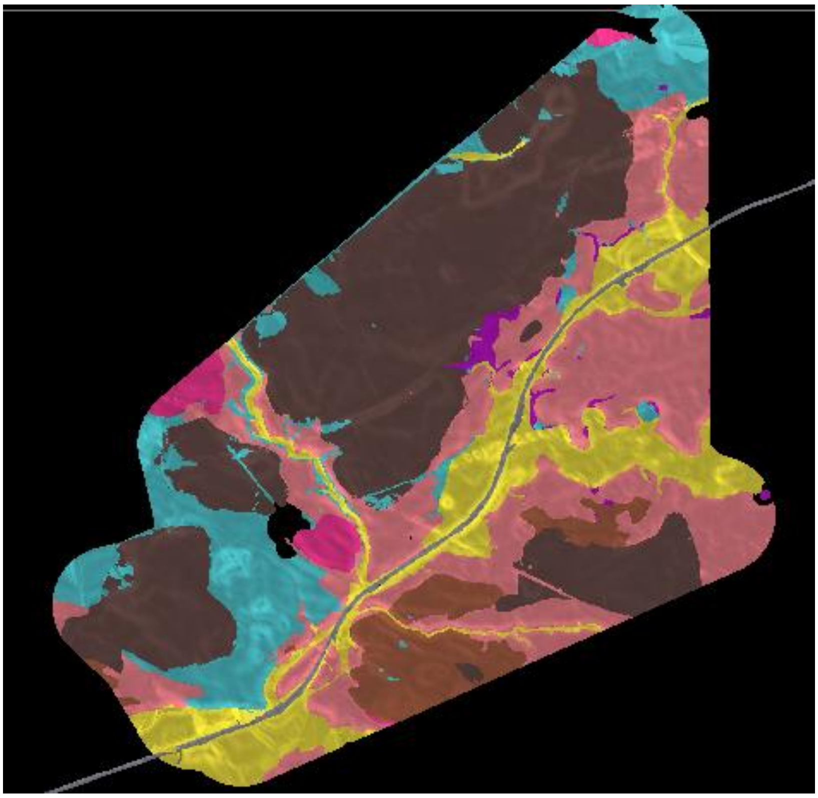

**Figure 12** 3D view of the Irlam area from above, showing superficial deposits and artificially modified ground, vertical exaggeration x10. Legend as per Table 1

# 13 References

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# Appendix 1 Model development log

Three versions of the model have been created.

1. Individual models constructed for Liverpool (2011), Warrington (2009) and Irlam (2012)
2. These were joined in 2015 as one 3D geological model but using a NextMap DTM as the capping surface
3. The model was rectified using the checking documentation from a QA of the individual models and updated using the OS Terrain 50 DTM/bathymetry as the capping surface

# Appendix 2 Boreholes used in the bedrock model.

The stratigraphic bases used in the bedrock model were interpreted directly in SKUA GOCAD. Below are the stratigraphic bases that were used in the 3D model.

| Borehole number (BGS_ID) | Easting | Westing | Elevation of base (m OD) | Measured depth in borehole (m) | Stratigraphic base |
|---|---|---|---|---|---|
| 503 | 332585 | 401299 | -675.12 | 687 | SHERWOOD_SANDSTONE_GROUP |
| 503 | 332585 | 401299 | -754.08 | 765.96 | CUMBRIAN_COAST_GROUP |
| 152086 | 328340 | 390880 | -272.49 | 281.63 | SHERWOOD_SANDSTONE_GROUP |
| 152086 | 328340 | 390880 | -682.8 | 691.94 | CUMBRIAN_COAST_GROUP |
| 157835 | 335120 | 389130 | -5.21 | 29.3 | MERCIA_MUDSTONE_GROUP |
| 163782 | 349750 | 386900 | -345.8 | 371.8 | SHERWOOD_SANDSTONE_GROUP |
| 163782 | 349750 | 386900 | -559 | 585 | WARWICKSHIRE_GROUP |
| 163799 | 345390 | 388162 | -232.15 | 243 | SHERWOOD_SANDSTONE_GROUP |
| 163799 | 345390 | 388162 | -368.15 | 379 | WARWICKSHIRE_GROUP |
| 163800 | 348030 | 387290 | -368.87 | 386.27 | SHERWOOD_SANDSTONE_GROUP |
| 163801 | 346640 | 385530 | -400.86 | 412 | SHERWOOD_SANDSTONE_GROUP |
| 163801 | 346640 | 385530 | -503.86 | 515 | WARWICKSHIRE_GROUP |
| 163802 | 348290 | 386520 | -380.35 | 398.5 | SHERWOOD_SANDSTONE_GROUP |
| 163802 | 348290 | 386520 | -529.85 | 548 | WARWICKSHIRE_GROUP |
| 164241 | 344850 | 386310 | -53 | 51.21 | SHERWOOD_SANDSTONE_GROUP |
| 164607 | 347964 | 384935 | -331.2 | 344 | SHERWOOD_SANDSTONE_GROUP |
| 164607 | 347964 | 384935 | -481.2 | 494 | WARWICKSHIRE_GROUP |
| 164887 | 347490 | 399680 | -316.94 | 317.3 | PENNINE_COAL_MEASURES_GROUP |
| 164888 | 349052 | 399345 | -280.69 | 281 | PENNINE_COAL_MEASURES_GROUP |
| 164889 | 345780 | 399330 | -120.54 | 121 | PENNINE_COAL_MEASURES_GROUP |
| 164988 | 340604 | 396135 | -86.83 | 85.04 | SHERWOOD_SANDSTONE_GROUP |
| 164988 | 340604 | 396135 | -121.11 | 119.32 | CUMBRIAN_COAST_GROUP |
| 164988 | 340604 | 396135 | -189.55 | 187.76 | APPLEBY_GROUP |
| 164988 | 340604 | 396135 | -223.53 | 221.74 | WARWICKSHIRE_GROUP |
| 164988 | 340604 | 396135 | -386.14 | 384.35 | PENNINE_COAL_MEASURES_GROUP |
| 165701 | 348630 | 390509 | -31 | 100 | SHERWOOD_SANDSTONE_GROUP |
| 165701 | 348630 | 390509 | -90 | 159 | CUMBRIAN_COAST_GROUP |
| 166803 | 359950 | 376030 | -639.91 | 640 | MERCIA_MUDSTONE_GROUP |
| 166870 | 353350 | 379100 | -188.062 | 195.072 | MERCIA_MUDSTONE_GROUP |
| 167131 | 355310 | 386160 | -404.92 | 405 | SHERWOOD_SANDSTONE_GROUP |
| 167138 | 356635 | 389020 | -192.07 | 206 | SHERWOOD_SANDSTONE_GROUP |
| 167138 | 356635 | 389020 | -291.45 | 305.38 | CUMBRIAN_COAST_GROUP |
| 167138 | 356635 | 389020 | -453.35 | 467.28 | APPLEBY_GROUP |
| 167138 | 356635 | 389020 | -597.651 | 611.5812 | WARWICKSHIRE_GROUP |
| 168308 | 353666 | 387969 | -241.7 | 264.26 | SHERWOOD_SANDSTONE_GROUP |
| 168310 | 352550 | 387310 | -22.68 | 55.8 | SHERWOOD_SANDSTONE_GROUP |
| 168310 | 352550 | 387310 | -105.48 | 138.6 | APPLEBY_GROUP |
| 168321 | 351094 | 386980 | -51.6 | 82.6 | SHERWOOD_SANDSTONE_GROUP |

| | | | | | |
|---|---|---|---|---|---|
| 168321 | 351094 | 386980 | -147 | 178 | SHERWOOD_SANDSTONE_GROUP |
| 168321 | 351094 | 386980 | -243.6 | 274.6 | APPLEBY_GROUP |
| 168321 | 351094 | 386980 | -364 | 395 | WARWICKSHIRE_GROUP |
| 168324 | 354723 | 388975 | -56 | 77.4 | SHERWOOD_SANDSTONE_GROUP |
| 168324 | 354723 | 388975 | -270 | 291.4 | SHERWOOD_SANDSTONE_GROUP |
| 168324 | 354723 | 388975 | -285.6 | 307 | CUMBRIAN_COAST_GROUP |
| 168324 | 354723 | 388975 | -445.7 | 467.1 | APPLEBY_GROUP |
| 168324 | 354723 | 388975 | -603.4 | 624.8 | WARWICKSHIRE_GROUP |
| 168354 | 353451 | 386782 | -373.11 | 396 | SHERWOOD_SANDSTONE_GROUP |
| 168354 | 353451 | 386782 | -707.11 | 730 | WARWICKSHIRE_GROUP |
| 168358 | 353220 | 387930 | -219.22 | 256 | SHERWOOD_SANDSTONE_GROUP |
| 168358 | 353220 | 387930 | -420.22 | 457 | WARWICKSHIRE_GROUP |
| 168762 | 354140 | 389400 | -191.46 | 214 | SHERWOOD_SANDSTONE_GROUP |
| 168762 | 354140 | 389400 | -207.46 | 230 | CUMBRIAN_COAST_GROUP |
| 168762 | 354140 | 389400 | -327.46 | 350 | APPLEBY_GROUP |
| 168762 | 354140 | 389400 | -485.46 | 508 | WARWICKSHIRE_GROUP |
| 168763 | 354321 | 388514 | -237.6 | 256 | SHERWOOD_SANDSTONE_GROUP |
| 168763 | 354321 | 388514 | -252.6 | 271 | CUMBRIAN_COAST_GROUP |
| 168763 | 354321 | 388514 | -394.6 | 413 | APPLEBY_GROUP |
| 168763 | 354321 | 388514 | -539.6 | 558 | WARWICKSHIRE_GROUP |
| 171237 | 355660 | 393490 | -98.36 | 98.7 | SHERWOOD_SANDSTONE_GROUP |
| 171237 | 355660 | 393490 | -112.46 | 112.8 | CUMBRIAN_COAST_GROUP |
| 171237 | 355660 | 393490 | -135.96 | 136.3 | APPLEBY_GROUP |
| 171240 | 359010 | 394790 | -209.22 | 209.4 | SHERWOOD_SANDSTONE_GROUP |
| 171240 | 359010 | 394790 | -246.38 | 246.56 | CUMBRIAN_COAST_GROUP |
| 171240 | 359010 | 394790 | -261.41 | 261.59 | APPLEBY_GROUP |
| 171240 | 359010 | 394790 | -325.42 | 325.6 | WARWICKSHIRE_GROUP |
| 171293 | 357617 | 391651 | -273.6 | 288 | SHERWOOD_SANDSTONE_GROUP |
| 171293 | 357617 | 391651 | -319.6 | 334 | CUMBRIAN_COAST_GROUP |
| 171293 | 357617 | 391651 | -437.6 | 452 | APPLEBY_GROUP |
| 171293 | 357617 | 391651 | -619.9 | 634.3 | WARWICKSHIRE_GROUP |
| 171294 | 359061 | 392324 | -305.7 | 319 | SHERWOOD_SANDSTONE_GROUP |
| 171294 | 359061 | 392324 | -344.7 | 358 | CUMBRIAN_COAST_GROUP |
| 171294 | 359061 | 392324 | -428.7 | 442 | APPLEBY_GROUP |
| 171294 | 359061 | 392324 | -716.7 | 730 | WARWICKSHIRE_GROUP |
| 171295 | 357197 | 393549 | -251.8 | 277 | SHERWOOD_SANDSTONE_GROUP |
| 171295 | 357197 | 393549 | -276.8 | 302 | CUMBRIAN_COAST_GROUP |
| 171295 | 357197 | 393549 | -342.8 | 368 | APPLEBY_GROUP |
| 171295 | 357197 | 393549 | -370.8 | 396 | WARWICKSHIRE_GROUP |
| 172994 | 354860 | 393500 | -53.01 | 53.44 | APPLEBY_GROUP |
| 172994 | 354860 | 393500 | -156.57 | 157 | WARWICKSHIRE_GROUP |
| 639643 | 377373 | 383541 | -275.83 | 276.15 | MERCIA_MUDSTONE_GROUP |
| 639646 | 376961 | 382331 | -138.31 | 138.68 | MERCIA_MUDSTONE_GROUP |
| 749082 | 370269 | 377851 | -713.4 | 753 | MERCIA_MUDSTONE_GROUP |
| 749082 | 370269 | 377851 | -1838.4 | 1878 | SHERWOOD_SANDSTONE_GROUP |
| 749082 | 370269 | 377851 | -2225.9 | 2265.5 | CUMBRIAN_COAST_GROUP |

| | | | | | |
|---|---|---|---|---|---|
| 761783 | 361991 | 395730 | -126.03 | 160.02 | SHERWOOD_SANDSTONE_GROUP |
| 761783 | 361991 | 395730 | -159.86 | 193.85 | CUMBRIAN_COAST_GROUP |
| 761783 | 361991 | 395730 | -251.91 | 285.9 | APPLEBY_GROUP |
| 761783 | 361991 | 395730 | -267.914 | 301.9044 | WARWICKSHIRE_GROUP |
| 765870 | 374640 | 397875 | -58.64 | 80.47 | SHERWOOD_SANDSTONE_GROUP |
| 765870 | 374640 | 397875 | -105.58 | 127.41 | APPLEBY_GROUP |
| 765870 | 374640 | 397875 | -360.542 | 382.3716 | WARWICKSHIRE_GROUP |
| 765872 | 372121 | 397572 | -240.24 | 240.49 | SHERWOOD_SANDSTONE_GROUP |
| 765872 | 372121 | 397572 | -257.31 | 257.56 | SHERWOOD_SANDSTONE_GROUP |
| 765872 | 372121 | 397572 | -304.63 | 304.88 | CUMBRIAN_COAST_GROUP |
| 765872 | 372121 | 397572 | -420.247 | 420.497 | WARWICKSHIRE_GROUP |
| 765947 | 371810 | 396285 | -260.21 | 287 | SHERWOOD_SANDSTONE_GROUP |
| 765947 | 371810 | 396285 | -281.21 | 308 | SHERWOOD_SANDSTONE_GROUP |
| 765947 | 371810 | 396285 | -331.21 | 358 | CUMBRIAN_COAST_GROUP |
| 765947 | 371810 | 396285 | -416.21 | 443 | APPLEBY_GROUP |
| 765947 | 371810 | 396285 | -571.21 | 598 | WARWICKSHIRE_GROUP |
| 792791 | 368990 | 396820 | -287.4 | 310.02 | SHERWOOD_SANDSTONE_GROUP |
| 792791 | 368990 | 396820 | -330 | 352.62 | CUMBRIAN_COAST_GROUP |
| 792791 | 368990 | 396820 | -414.38 | 437 | APPLEBY_GROUP |
| 792791 | 368990 | 396820 | -507.38 | 530 | WARWICKSHIRE_GROUP |
| 792796 | 366271 | 395281 | -495.2 | 522 | SHERWOOD_SANDSTONE_GROUP |
| 792796 | 366271 | 395281 | -544.2 | 571 | APPLEBY_GROUP |
| 792796 | 366271 | 395281 | -744.2 | 771 | WARWICKSHIRE_GROUP |
| 793123 | 369985 | 395356 | -401.51 | 428 | SHERWOOD_SANDSTONE_GROUP |
| 793123 | 369985 | 395356 | -421.51 | 448 | SHERWOOD_SANDSTONE_GROUP |
| 793123 | 369985 | 395356 | -475.51 | 502 | CUMBRIAN_COAST_GROUP |
| 793123 | 369985 | 395356 | -619.51 | 646 | WARWICKSHIRE_GROUP |
| 793124 | 368248 | 398907 | -134.53 | 159 | APPLEBY_GROUP |
| 793124 | 368248 | 398907 | -201.53 | 226 | WARWICKSHIRE_GROUP |
| 819276 | 362910 | 383410 | -107.8 | 108.5 | MERCIA_MUDSTONE_GROUP |
| 822636 | 367516 | 389865 | -531.76 | 555 | SHERWOOD_SANDSTONE_GROUP |
| 822636 | 367516 | 389865 | -576.76 | 600 | CUMBRIAN_COAST_GROUP |
| 822636 | 367516 | 389865 | -681.76 | 705 | APPLEBY_GROUP |
| 822636 | 367516 | 389865 | -698.76 | 722 | WARWICKSHIRE_GROUP |
| 943687 | 362720 | 390200 | -140.22 | 150 | SHERWOOD_SANDSTONE_GROUP |
| 943687 | 362720 | 390200 | -504.33 | 514.11 | CUMBRIAN_COAST_GROUP |
| 943687 | 362720 | 390200 | -631.93 | 641.71 | APPLEBY_GROUP |
| 943687 | 362720 | 390200 | -862.22 | 872 | WARWICKSHIRE_GROUP |
| 943688 | 360330 | 390010 | -463.77 | 473 | SHERWOOD_SANDSTONE_GROUP |
| 943688 | 360330 | 390010 | -493.77 | 503 | CUMBRIAN_COAST_GROUP |
| 943688 | 360330 | 390010 | -527.77 | 537 | APPLEBY_GROUP |
| 943688 | 360330 | 390010 | -699.27 | 708.5 | WARWICKSHIRE_GROUP |
| 943689 | 363620 | 392540 | -259.17 | 276 | SHERWOOD_SANDSTONE_GROUP |
| 943689 | 363620 | 392540 | -273.17 | 290 | CUMBRIAN_COAST_GROUP |
| 943689 | 363620 | 392540 | -292.17 | 309 | APPLEBY_GROUP |
| 943689 | 363620 | 392540 | -473.17 | 490 | WARWICKSHIRE_GROUP |

| | | | | | |
|---|---|---|---|---|---|
| 943692 | 364470 | 394130 | -356.37 | 393 | SHERWOOD_SANDSTONE_GROUP |
| 943692 | 364470 | 394130 | -409.37 | 446 | CUMBRIAN_COAST_GROUP |
| 943692 | 364470 | 394130 | -602.37 | 639 | APPLEBY_GROUP |
| 943712 | 362131 | 391574 | -251.25 | 268 | SHERWOOD_SANDSTONE_GROUP |
| 943712 | 362131 | 391574 | -277.25 | 294 | APPLEBY_GROUP |
| 943712 | 362131 | 391574 | -485.25 | 502 | WARWICKSHIRE_GROUP |
| 945047 | 364381 | 390995 | -423 | 438 | SHERWOOD_SANDSTONE_GROUP |
| 945047 | 364381 | 390995 | -461 | 476 | CUMBRIAN_COAST_GROUP |
| 945047 | 364381 | 390995 | -553 | 568 | APPLEBY_GROUP |
| 945047 | 364381 | 390995 | -749 | 764 | WARWICKSHIRE_GROUP |
| 954339 | 376271 | 399139 | -89.8234 | 116.1034 | WARWICKSHIRE_GROUP |
| 954340 | 375407 | 398565 | -82.32 | 103.02 | SHERWOOD_SANDSTONE_GROUP |
| 954340 | 375407 | 398565 | -152.73 | 173.43 | WARWICKSHIRE_GROUP |
| 954849 | 376400 | 399770 | -38.81 | 65.1 | PENNINE_COAL_MEASURES_GROUP |
| 19206308 | 346211 | 376439 | -267.318 | 277.368 | SHERWOOD_SANDSTONE_GROUP |
| 19206308 | 346211 | 376439 | -387.714 | 397.764 | WARWICKSHIRE_GROUP |
| 19206308 | 346211 | 376439 | -934.829 | 944.879 | PENNINE_COAL_MEASURES_GROUP |
| 19206308 | 346211 | 376439 | -1270.11 | 1280.159 | MILLSTONE_GRIT_GROUP |
| 19415659 | 374200 | 399800 | -1.55 | 22.55 | CUMBRIAN_COAST_GROUP |
| 19415665 | 374300 | 399770 | -2.23 | 23.83 | CUMBRIAN_COAST_GROUP |
| 20742309 | 377343 | 388001 | 12.92 | 15.62 | MERCIA_MUDSTONE_GROUP |