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Clyde superficial deposits and bedrock models released to the ASK Network 2013 : a guide for users Version 2

Geology and Regional Geophysics Programme

Open Report OR/13/025

BRITISH GEOLOGICAL SURVEY

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Summary

This report provides an overview of all the Clyde superficial deposits and bedrock models to be released to the ASK (Accessing Subsurface Knowledge) knowledge exchange network in January and June 2013. The geological models are an interpretation of digital datasets held by the British Geological Survey.

A summary of the construction and limitations of the models and a brief description of the modelled units is given. The report will be updated and revised as more models become available for release to the ASK network.

More details on the models can be found in the reports Merritt et al. (2009), Monaghan (2012a), Monaghan et al. (2012), McCormac (2013) and Arkley et al. (2013).

1 Modelled volume, purpose and scale

1.1 SUPERFICIAL DEPOSITS

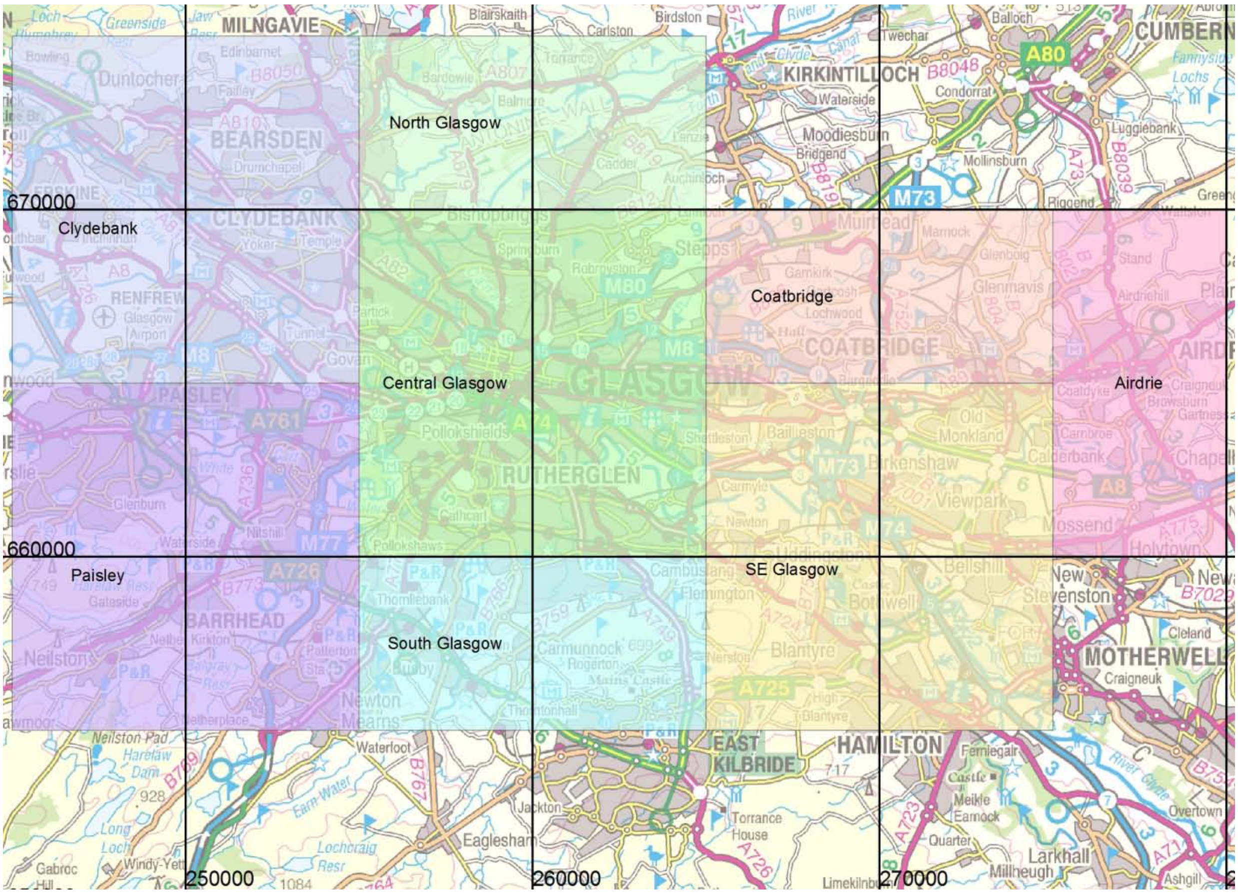

Figure 1 Superficial deposits model areas.

The Superficial Deposits Models of the Glasgow area were constructed in tiled areas (Figure 1) for reasons of computing power and software capability. In January 2013, the Central Glasgow tile was released to the ASK (Accessing Subsurface Knowledge) knowledge exchange network which has the corner coordinates SW 255000, 660000 to NE 265000, 670000. Now available (June 2013) to the ASK Network are superficial deposits models with corner coordinates SW 245000, 655000 to NW 265000, 675000 comprising the South Glasgow, Paisley, Clydebank, and North Glasgow models. Note that due to data availability, the Clydebank and South Glasgow models do not cover the full sheet extents as implied in Figure 1. The remaining models will be released in due course. The model Z values or depths are all given in metres relative to Ordnance Datum (OD) and range from approximately +230 to -80 m.

The Superficial Deposits Models are most suitable for use at scales between 1:10 000 to 1:50 000 but are also useful for providing guidance at other scales.

The purpose of the Superficial Deposits Models is to give a broad indication of the likely subsurface sequence from Devensian glacial till to artificial (man-made) deposits across Glasgow for use during the desk study stage, in for example the assessment of potential infrastructure alignments and locations, and relatively broad scales of planning. However, the model is also well suited to act as a *guide* for studies at more detailed scales, and especially as a basis for planning and improving the economic efficiency of, site investigations. However, users are advised against basing interpretations on extreme exaggeration of the vertical or horizontal scales of the models.

The Superficial Deposits Models were improved in 2012/13 to be fully consistent with surrounding models and to include some new cross-sections in the south-west part of the model, compared to earlier versions supplied by the British Geological Survey to Clyde Gateway

Developments Ltd, Glasgow City Council, South Lanarkshire Council and Scottish Enterprise (see section 4.1 below). Versions supplied to the ASK Network in June 2013 are version 3 of the Central Glasgow model and version 2 of the surrounding tiles.

1.2 BEDROCK

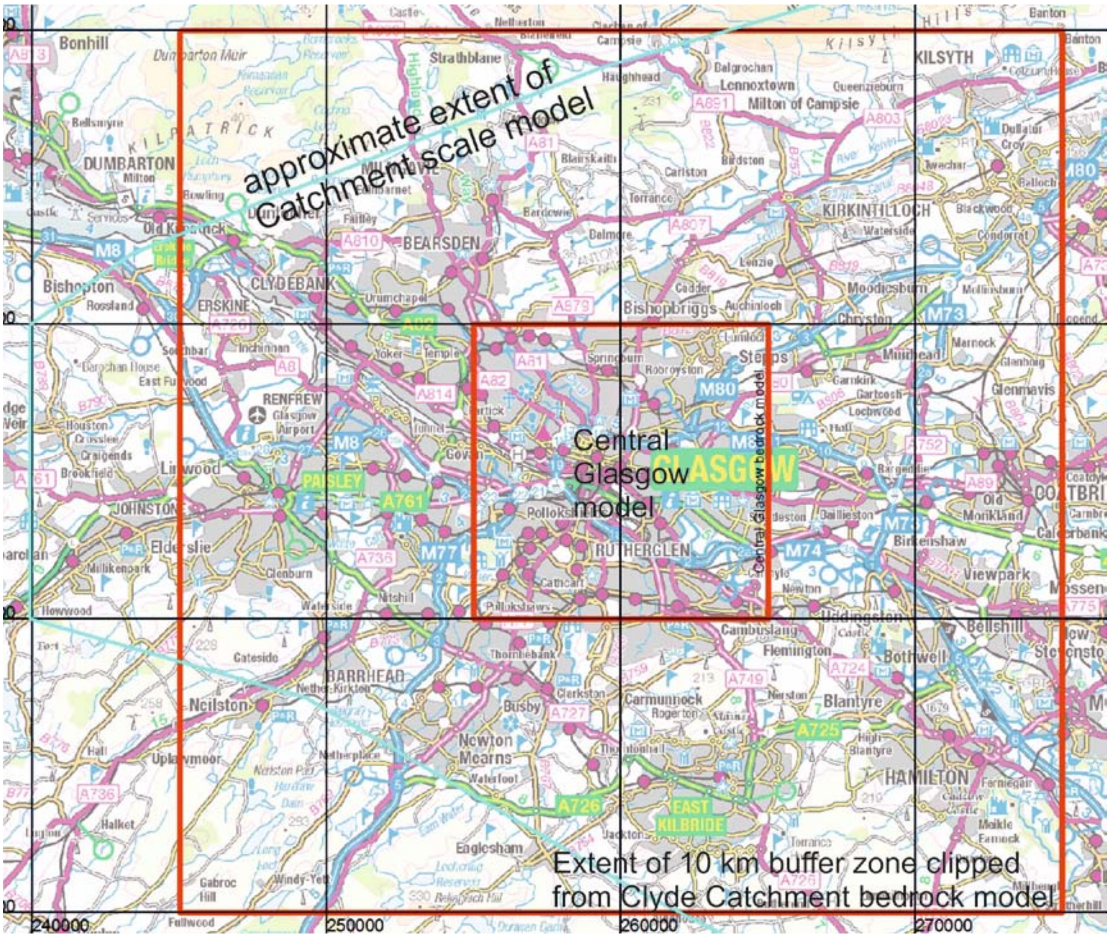

Figure 2 Image showing the extent of the Central Glasgow Bedrock Model and the extent of the lower resolution Clyde Catchment scale bedrock model (blue), provided to the ASK Network as a clipped 10 km buffer around the Central Glasgow bedrock model.

Bedrock modelling has been undertaken at a variety of scales by the British Geological Survey in the Clyde Catchment. The model scale is dependent on the data available and used, the number of coal seams, stratigraphic surfaces and faults included in the model.

The Central Glasgow Bedrock Model provided to the ASK network is the same as the Version 2 model supplied to Clyde Gateway Developments Ltd, Glasgow City Council, South Lanarkshire Council and Scottish Enterprise in early 2012. It has the corner coordinates SW 255000, 660000 to NE 265000, 670000. A lower resolution Clyde Catchment scale bedrock model is also now provided with the corner coordinates SW 250000, 655000 to NE 270000, 680000. The model Z values or depths are all given in metres relative to Ordnance Datum (OD) with the modelled surfaces extending to c.-1100 m depth, with the largest faults projecting down to c. -2.5 km

The Central Glasgow Bedrock Model is most suitable for use at scales from 1:10 000 to 1:50 000 but is also useful for providing guidance at other scales. The Clyde Catchment scale model provided for the buffer zone is most suitable for use at scales between 1:100 000 to 1:250 000.

Note that because the Clyde Catchment bedrock model was undertaken at a different scale from the Central Glasgow bedrock model, contains fewer faults and larger mesh/grid spacing, the two models are not edge matched. The Clyde Catchment bedrock model has simply been cut to the

10 km buffer zone (Figure 2) provided to the ASK Network, that is, the Z value of the modelled horizons is not necessarily the same at any given point along the model boundary and the fault positions do match exactly in 3D space. The maximum difference is of the order of 20 m on the Glasgow Ell (GE) surface and 90 m on the base Upper Limestone Formation (bULGS) surface. These differences give an indication of the model uncertainty at depth where the modelled surfaces are poorly constrained by borehole or mine plan data.

The purpose of the bedrock models was to specify in 3D the geometry and faulting of some key, mined coal seams for use in outline planning and development, and key stratigraphic surfaces for regional geological correlation.

1.3 DATASETS PROVIDED TO USERS

The Superficial Deposits Models were created in the GSI3D modelling software and have been converted to ASCII grids and ESRI (ArcGIS) raster grids for supply to users, and encrypted within Lithoframe Viewer software for 3D visualisation, synthetic sections and boreholes.

For the ASCII grids, these are provided in folders by block model area and with a base (e.g. witi_dmtn_b.asc), top (e.g. witi_dmtn_t.asc) and thickness (e.g. witi_dmtn_th.asc). Lenses only have a top.

The stratigraphic and rock type codes used in the exported model grids are described in section 2. In addition the qualifiers _t, _b and _th are used to indicate the unit top, base and thickness respectively.

For the ESRI grids, the base (e.g. witi_dmtn_b) and top (e.g. witi_dmtn_t) have been merged across the whole of the 5 block model areas. Outlines of the modelled unit extent (‘envelope’) are supplied as ESRI shapefiles across the 5 block areas (and beyond).

The resolution of the superficial deposit ASCII and ESRI grids is 25 m.

The Lithoframe Viewer software and an accompanying manual can be downloaded from the BGS website at http://www.bgs.ac.uk/services/3Dgeology/lithoframeSamples.html. Note that in some versions of Windows it is necessary to paste in the .GSIPRe file location and name to the ‘Load model’ screen, loading of the models and refreshing of the 3D window may take a few minutes, and that creating a horizontal slice in the Lithoframe Viewer takes a considerable time (20 minutes).

The Central Glasgow and Clyde Catchment scale bedrock models were created in the GOCAD® modelling software and have been converted to ESRI grids for supply to users. The surface grids and a combined fault grid were exported from the modelled GOCAD® TIN’s using a grid spacing of 25 m for the Central Glasgow bedrock model and 50 m for the Clyde Catchment scale bedrock model. The stratigraphic codes used for naming the modelled surfaces are described in section 2.

Examples of uncertainty layers are also provided as images or ASC files; these are described further in section 8 of this report. Further uncertainty layers will be provided to the ASK Network on delivery of all the superficial deposits models.

2 Modelled surfaces/volumes

2.1 SUPERFICIAL DEPOSITS

Code	Geological Unit	Equivalent description on 1: 10, 000 scale published map
Water	Water	Unattributed polygons or underlying sediments described
MGR-ARTDP	Made Ground (made and worked ground undifferentiated)	Made Ground (MGR), Made Ground and Worked Ground (WMGR), Infilled Ground (WMGR)
HEAD-XCZSV	Head	Not recorded on the maps covered by the model, would be described as Head, Flandrian (HEAD)
PEAT-P	Peat	Peat – blanket or basin peat, Flandrian (PEAT)
LDE-XCZSP	Lacustrine deposit	Lacustrine Deposits, Flandrian (LDE)
LAWSG-XCZSVP	Law Sand and Gravel Member	Alluvium – modern river floodplains – located along the upper reaches and tributaries to the River Clyde, Flandrian (ALV). Also includes some Alluvial Fan Deposits, Flandrian (ALF) and some River Terrace Deposits, Flandrian (RTD1 and RTD2)
KELV-XCZSP	Strathkelvin Sand and Silt Member	Alluvium – modern river floodplains – mainly tributaries located north of the River Clyde, Flandrian (ALV) and Lacustrine Deposits, Flandrian (LDE)
GOSA-XCZSV	Gourock Sand Member	Marine Deposits – located along the lower reaches of the River Clyde, Flandrian (MDU) and Alluvium – modern river floodplains – along the upper reaches of the River Clyde, Flandrian (ALV)
ERSK-XCZ	Erskine Clay Member	Not recorded on the maps covered by the model (concealed beneath younger deposits), identified at depth from borehole data
LUGH-XSV	Longhaugh Sand and Gravel Member	Not recorded on the maps covered by the model (concealed beneath younger deposits), identified at depth from borehole data
INVN-BLVC	Innerleven Gravel Member	Not recorded on the maps covered by the model (concealed beneath younger deposits), identified at depth from borehole data
KARN-XSV	Killearn Sand and Gravel Member	Generally Raised Marine Deposits, Devensian (RMDV), Raised Marine Deltaic Deposits, Devensian (RMDDD) or Raised Marine Intertidal and Subtidal Deposits, Devensian (RMIS)
LIWD-XCZS	Linwood Clay Member	Generally Raised Marine Deposits, Devensian (RMDV) or Raised Marine Intertidal and Subtidal Deposits, Devensian (RMIS)
PAIS-XCZS	Paisley Clay Member	Generally Raised Marine Deposits, Devensian (RMDV) or Raised Marine Intertidal and Subtidal Deposits, Devensian (RMIS)
BRON-XSVZ	Bridgeton Sand Member	Largely concealed beneath younger deposits, where present, exposures usually represented as Raised Marine Deposits, Devensian (RMDV)
BILL2-XZCS	Bellshill Clay Member	Glaciolacustrine Deposits, Devensian (GLLDD)
RSSA-XSV	Ross Sand Member	Glaciolacustrine Deposits, Devensian (GLLDD), Glaciolacustrine Deltaic Deposits, Devensian (GLDDD) or Glaciofluvial Deposits, Devensian (GFDUD)
RSSA-XSZ	Ross Sand Member (silt, sand)	Largely concealed beneath younger deposits, identified at depth from borehole data, rare exposures represented as Glaciolacustrine Deposits, Devensian (GLLDD) or Glaciolacustrine Deltaic Deposits, Devensian (GLDDD)

BILL1-XZCS	Bellshill Clay Member	Glaciolacustrine Deposits, Devensian (GLLDD)
BHSE-XSV	Broomhouse Sand and Gravel Formation (sand and gravel)	Largely concealed beneath younger deposits, where present, exposures usually represented as Glaciofluvial Deposits, Devensian (GFDUD), but also as Glaciofluvial Ice-Contact Deposits, Devensian (GFICD)
BHSE-S	Broomhouse Sand and Gravel Formation (sand)	Not recorded on the maps covered by the model (concealed beneath younger deposits), identified at depth from borehole data
WITI-DMTN	Wilderness Till Formation	Till - Devensian (TILLD)
SUPD-XZC	Clay and silt	Not recorded on the maps covered by the model (concealed beneath younger deposits), identified at depth from borehole data
CADR-XSV	Cadder Sand and Gravel Formation	Generally concealed beneath younger deposits, identified at depth from borehole data, rare exposures represented as Glaciofluvial Deposits, Devensian (GFDUD)
BRLL-XCZ	Broomhill Clay Formation	Not recorded on the maps covered by the model (concealed beneath younger deposits), identified at depth from borehole data
BNTI-DMTN	Baillieston Till Formation	Not recorded on the maps covered by the model (concealed beneath younger deposits), identified at depth from borehole data
SUPD-XSV	Sand and gravel	Not recorded on the maps covered by the model (concealed beneath younger deposits), identified at depth from borehole data
SUPD-C	Clay	Not recorded on the maps covered by the model (concealed beneath younger deposits), identified at depth from borehole data

Table 1 Lithostratigraphic units included in the superficial deposits models over the Glasgow area in stratigraphic order.

Table 1 indicates the lithostratigraphic units in the Superficial Deposits Models. In Table 1, X indicates that each lithology is represented (e.g. XSV is a unit containing sand and gravel as opposed to SV which would be a gravelly sand), where S=sand, C=clay, Z=silt, V=gravel, DMTN= diamicton, ARTDP= artificial deposits, P= Peat. Some lenses are modelled in addition, as described below.

A description of each of the modelled units is given below in approximately ascending order.

2.2 BAILLIESTON TILL FORMATION (BNTI)

The Baillieston Till Formation rests directly on bedrock in the Clydebank and North Glasgow model areas and is overlain by the Broomhill Clay Formation, Cadder Sand and Gravel Formation, or an un-named silt unit. It consists of stiff to very stiff, red-brown, silty, sandy clay with gravel, cobbles, boulders and some sand layers. The Baillieston Till Formation is considered to be a pre late-Devensian till.

2.3 BROOMHILL CLAY FORMATION (BRLL)

The Broomhill Clay Formation consists of laminated clayey-silt with sandy partings and rests directly on bedrock or is underlain by the Ballieston Till. It is overlain by the dense sand and gravel of the Cadder Sand and Gravel Formation.

2.4 CADDER SAND AND GRAVEL FORMATION (CADR)

The Cadder Sand and Gravel Formation is found mainly to the north of the River Clyde, with deposits up to 60 m thick associated with the deep bedrock depressions of the Kelvin buried valley-system. In some areas (e.g. SE Glasgow) the unit has been truncated by the emplacement of overlying tills and by modern river erosion, resulting in modification of the original depositional morphology of the unit.

The Cadder Sand and Gravel Formation consists of bedded and trough cross-bedded dense sand or silty sand, with gravel and some cobbles. There are occasional clay lenses. Cross bedding has been described in exposed outcrops in the Kelvin Valley. Significant deformation of the upper parts of the unit has occurred due to overriding of the Late Devensian ice sheet (Wilderness Till). The Cadder Sand and Gravel Formation is thought to have originated as outwash deposits, possibly fluvial or deltaic, formed in front of the advancing late Devensian ice sheet. The sands have yielded bones and teeth of woolly rhinoceros, from which Rolfe (1966) reported a radiocarbon age of 27.5 ^{14}C ka BP.

2.4.1 Silt Unit (SUPD_XZC)

A small, un-named silt unit consisting of a firm to stiff, red-brown clay or silty clay with a little sand, overlies the Cadder Sand and Gravel Formation in places. It has silt laminations and may contain sand seams and traces of fine gravel. The unit contains a till lense and is overlain by the Wilderness Till Formation. It may represent deposition from pro-glacial lakes developing in association with Cadder Formation sand and gravel as the Late Devensian ice sheet advanced up the Firth of Clyde and into the Clyde Valley.

2.5 WILDERNESS TILL FORMATION (WITI)

The Late Devensian Wilderness Till Formation is the most extensive unit in the Clyde area and is named after temporary sections seen in the Wilderness Plantation area north of Bishopbriggs. It is characterised by a diamicton comprising isolated boulders, gravel and cobbles in a firm to stiff sandy, silty to clayey matrix (Browne and McMillan, 1989). Commonly it rests directly on bedrock, but is underlain in places by the Cadder Sand and Gravel, Broomhill Clay or Ballieston Till formations. Drumlins, which are large mounds formed during emplacement of the till below moving glacier ice, are a characteristic landform associated with the Wilderness Till Formation. Drumlins constrain the hilly terrain of Central Glasgow and the surrounding areas where the Wilderness Till is exposed at the surface. Along the Clyde valley, buried drumlins cause considerable spatial variation in the thickness of overlying sediment deposits.

2.6 BROOMHOUSE SAND AND GRAVEL FORMATION (BHSE)

The Broomhouse Sand and Gravel is named after the Broomhouse area of eastern Glasgow where it generally overlies the Wilderness Till Formation. It comprises glaciofluvial ice-contact deposits, which produce features such as esker ridges, mounds, isolated flat-topped kames and kettleholes. Overall, the most abundant deposit is sand, except in esker ridges where gravel dominates. In some places it may also contain cobbles, clay and silt. The sands are planar and trough cross-bedded, ripple laminated and horizontally laminated; the gravels are typically massive or crudely bedded. Deposits are up to 25 m thick and flow directions were towards the east (Browne and MacMillan, 1989). The noted occurrences of Broomhouse Sand and Gravel Formation are coincident with areas of dense borehole data. This implies that there may be more extensive deposits in the area than have been modelled, but a lack of data means that further deposits remain undetected. The Broomhouse Sand and Gravel Formation includes three members: the Bellshill Clay Member, the Greenoakhill Sand and Gravel Member and the Ross Sand Member. The Bellshill Clay and Ross Sand members have been modelled separately.

2.6.1 Bellshill Clay Member (BILL1 and BILL2)

The Bellshill Clay Member, a member of the Broomhouse Sand and Gravel Formation, comprises silt-clay with wisps, laminae and bands of silt and sometimes sand, deposited, along with the coarser-grained Ross Sand Member (described below), in lakes forming at the margin of the Clyde glacier. The largest of these lakes, a pro-glacial lake called ‘Lake Clydesdale’, formed to the south-east of an ice margin marked by the ‘Blantyreferme terminal moraine’ (south-east of Glasgow) as the glacier retreated towards the north-west (Browne and McMillan, 1989). The area covered by ‘Lake Clydesdale’, located south of Bothwell, thus contains the most extensive development of the Bellshill Clay Member. Away from the Clyde valley, the Bellshill Clay Member is found in hollows in the Wilderness Till Formation drumlins. Its occurrence can be best explained by a level for Lake Clydesdale at about 62 m O.D., although it is found as high as 80 m O.D. in other areas.

Near the margins of the former glacial lake, the Bellshill Clay Member inter-fingers with coarser silty-sand and gravelly-sand of the Ross Sand Member, deposited in deltaic systems by meltwater streams entering Lake Clydesdale. The Bellshill Clay Member is thus found below, adjacent to, and in places above, the Ross Sand Member (e.g. Fig 3 of Browne and McMillan, 1989), and the relationship of the units has been simplified for modelling purposes by splitting the Bellshill Clay Member into two units that lie above (BILL2) and below (BILL1) the Ross Sand Member. The Bellshill Clay Member is overlain by the Bridgeton Sand Member, Paisley Clay Member and later alluvial deposits.

The following rules were used to model the Bellshill Clay Member:

1) The Bellshill Clay member is distinguished from the overlying Paisley Clay Member by the presence of intervening sand units and more abundant sandy laminae within the silt-clay strata.

2) The Bellshill Clay Member includes some lithologies coded in the BGS borehole database as diamicton. These are described in logs as clay rich gravel layers and are hypothesised to be boulder clay. The decision to include diamicton in this group is supported by descriptions of the Bellshill Clay Member lithologies in Browne and McMillan (1989). These units are interpreted to be thin till bands deposited during minor oscillations in the position of the ice front during the period of existence of Lake Clydesdale.

3) Where it outcrops at the surface, the Bellshill Clay Member is equivalent to the Glaciolacustrine Deltaic Devensian (GLDDD), consisting of silty clay with some predominant silt and sand partings, depicted on BGS digital 1:10 000 and 1:50 000 scale superficial geology maps (DiGMapGB).

2.6.2 Ross Sand Member (RSSA)

The main lithologies of the Ross Sand Member, a member of the Broomhouse Sand and Gravel Formation, are sand or sand and silt, with clays at the base and thin local gravel layers. As noted above, the deposits are glacio-lacustrine in origin with deposits found in the south-east of Glasgow interpreted to have formed in deltaic systems at the margins of glacial ‘Lake Clydesdale’ (Browne and MacMillan, 1989). For modelling purposes, the lithologies have been separated into two units, a main unit of sand with minor gravel (RSSA-XSV), and an underlying finer-grained sand with silt (RSSA-XSZ).

The Ross Sand Member is found draping the Wilderness Till Formation and is overlain by deposits of the Bridgeton Sand Member and Paisley Clay Member. Where it outcrops at the surface, the Ross Sand Member corresponds to glaciofluvial deltaic (and/or subaqueous fan) deposits (GFDD) on BGS DiGMapGB.

2.7 CLYDE CLAY FORMATION

The Clyde Clay Formation is part of the British Coastal Deposits Group and includes mainly Late Devensian deposits from marine isotope stages 2, 2a-b $\delta^{18}O$. The formation is modelled as component members including the Bridgeton Sand Member, the Paisley Clay Member, the Linwood Clay Member, the Killearn Sand and Gravel Member and the Innerleven Gravel Member.

2.7.1 Bridgeton Sand Member (BRON)

The Bridgeton Sand Member is characterised by fine to medium, massive dense sand or silty sand. Locally, fine to coarse gravel and boulders occur in a sandy matrix. There is some flat bedding but generally the deposits are massive. The unit is largely confined to the Clyde valley, where it overlies the Wilderness Till and Broomhouse Sand and Gravel formations. In the Clydebank area, The Bridgeton Sand Member is 20–30 m thick occupying a 2.5 km wide ‘strip’ confined by a bedrock depression following the line of the River Clyde. The deepest part of the depression, which contains the greatest thickness of the Bridgeton Sand Member, lies approximately 300–400 m to the south of the modern river.

Browne and MacMillan (1989) suggested that the sands were deposited as submarine outwash fans formed during catastrophic draining of pro-glacial Lake Clydesdale to the north-west along the line of the Clyde valley following breaching of the glacier dam.

2.7.2 Paisley Clay Member (PAIS)

The Paisley Clay Member comprises laminated clay and silt-clay deposited in a glaciomarine setting. In borehole records it is described as a grey and grey-brown, occasionally laminated, clayey silt and silty clay, often with a mottled appearance. The retreating glaciers are believed to have been to the north-west, in the sea lochs of the Southern Highlands. Relative sea level was high when deposition of the Paisley Clay Member commenced and some clays were deposited at elevations up to 40 m above OD (Browne and McMillan, 1989). The Paisley Clay Member drapes the underlying topography, and appears to thin out over the tops of drumlins (Wilderness Till Formation) and bedrock ‘highs’. To the south-east of Glasgow, all clay units at the ground surface within lowland areas (max. 40–45m O.D.) are assumed to be deposits of the Paisley Clay Member. All DiGMapGB polygons coded as raised marine deposits-Devensian (RMDV) were interpreted as outcrops of the Paisley Clay Member.

2.7.3 Linwood Clay Member (LIWD)

The Linwood Clay member overlies the Paisley Clay Member and consists of up to 35 m of clay or silt clay, with some sandy lenses and very sparse gravel. Occasional boulders encountered in some boreholes may be dropstones. The Linwood Clay Member is stratigraphically distinguished from the underlying Paisley Clay largely on the basis of an increase in the diversity of marine fossils contained within the strata (Browne and MacMillan, 1989). However, borehole logs rarely contain palaeontological information and thus the Paisley and Linwood Clay members are difficult to distinguish in many areas. Generally, the Linwood Clay Member is considered to be less laminated than the underlying Paisley Clay Member. In some areas, especially near outcrop, the Paisley Clay Member is orange to red-brown in colour, compared to the more grey-brown of the Linwood Clay. In an embayment of the palaeoshoreline in the vicinity of Paisley-Renfrew (much of sheet NS46NE), the Paisley Clay is significantly thinner than deposits found further east up the Clyde valley. By contrast, the Linwood Clay Member becomes more dominant in this area and is considerably thicker than the underlying Paisley Clay Member.

2.7.4 Killearn Sand and Gravel Member (KARN)

The Killearn Sand and Gravel Member is a patchy deposit comprising of varying proportions of sand and some clay layers. The deposits are commonly found in inter-drumlin areas along the Clyde Valley, and the distribution suggests that it formed as a result of marginal marine processes associated with the Late Devensian marine incursion responsible for the deposition of the Paisley and Linwood clays. The maximum level of the marine incursion thought to be responsible for the Killearn Member is approximately 34–36 m above OD (Browne and McMillan, 1989; Hall et al., 1998; Rose, 1975).

The Killearn Member is thought to have been deposited in a range of environments, including beaches, and fluvial and deltaic systems. Rose (1975) describes temporary sections north of

Erskine bridge where Killearn Member sands and gravels overlie Broomhouse Sand and Gravel Formation. Here the Killearn is well bedded, with beds displaying shallow dip to the south-west. It is suggested that the sedimentary structures are consistent with shoreline processes, hence that the unit in this area is a beach gravel. Rose (1975) also describes ice wedge casts suggesting that a periglacial environment persisted in the period following the deposition of the Killearn Member. It is suggested that these features may have formed during the cold period associated with the cooling event of the Younger Dryas. During this time, glaciers readvanced in the Loch Lomond area, but the Clyde remained ice free.

2.7.5 Inverleven Gravel Member (INVN)

The Inverleven Formation is a 0.5–2.5 m thick unit found in the lower part of the Clyde valley. It consists of boulders, cobbles and gravel in a sandy-clay matrix, and some shells and traces of barnacles on clasts have been found (Browne and McMillan, 1989). It is thought to be a lag deposit representing a Late Devensian erosive, or non-depositional phase in the Clyde Estuary. The Inverleven Gravel Member overlies eroded Linwood and/or Paisley Clay members and Wilderness Till Formation (Browne and McMillan, 1989).

2.8 CLYDEBANK CLAY FORMATION

2.8.1 Longhaugh Sand and Gravel Member (LUGH)

The Longhaugh Formation is known only from site investigation boreholes and there is no standard section for the unit (Browne and McMillan, 1989). It consists of silty-sand, with a little gravel, and some boulders towards the base. Some boreholes record shell debris, and this rarely noted characteristic is the only means of distinguishing it from the sand units of the underlying Bridgeton Sand Member and the overlying Gourock Sand Member.

The Longhaugh Formation appears to fill a pre-existing erosive channel aligned along the modern Clyde river, in places lined with coarse boulders and cobbles of the Inverleven Gravel Member. The channel cuts into older deposits, reaching a maximum depth of ~ -20 m OD. This stratigraphy suggests that the channel was cut, probably by tidal processes concentrated through the narrow Erskine gap during a marine incursion in the Late Devensian. It may have developed during a relative sea level fall (c.f Browne and McMillan, 1989 p15-16), either associated with the Loch Lomond Re-advance, or with the transition from marine to estuarine conditions that occurred in Late Devensian to early Flandrian times. This interpretation is consistent with the lack of occurrence of the Paisley and Linwood Clay Members in the lower parts of the Clyde Valley. Strong tidal currents may have prevented the deposition of fine clay and silt sediments in this area throughout the late Devensian, with the channel incision occurring at a low stand in sea level.

2.8.2 Erskine Clay Member (ERSK)

The Erskine Clay Member is the fine equivalent of the Flandrian age Gourock Sand Member, and is found in the valleys of the River Clyde and White and Black Cart Waters. It is distinguished from the underlying Linwood Clay Member because it contains significant organic matter. It is mainly found in association with the Gourock Sand Member, which overlies the Erskine Clay in a number of areas. The Erskine Clay Member overlies the Wilderness Till, Broomhouse Sand and Gravel Formation, Bridgeton Sand Member and the Longhaugh Sand and Gravel Member in the Clyde Valley, and the Linwood Clay Member in the valleys of the Black and White Cart. Small patches of peat may be developed on top of the Erskine Clay Member.

2.8.3 Gourock Sand Member (GOSA)

The Gourock Sand Member forms extensive deposits in the Clyde valley and as deposits along the Black and White Cart Waters. It consists of 0.5– ~5 m of fine to coarse sand with some gravel, silt and clay and organic detritus. It passes laterally in some areas into the Erskine Clay Member. The deposits are likely to have formed in estuarine environments, with a fluvial dominance in the east, becoming progressively more marine westwards with shallow channels linked by tidal flats (Browne and McMillan, 1989).

2.9 CLYDE VALLEY FORMATION

2.9.1 Strathkelvin Clay and Silt Member (KELV)

The Strathkelvin Clay and Silt Member is found largely within the Kelvin valley and as deposits along water courses to the north-east of Glasgow. The unit consists of a silt-clay containing abundant layers of silt and some sandy layers and lenses interbedded with peat. In general the clays are dark brown in colour and bands relatively rich in organic detritus also occur. The deposits are either of floodplain or lacustrine origin.

2.9.2 Law Sand and Gravel Member (LAWSG)

The Law Sand and Gravel Member comprises fine to coarse sand with some silt, fine gravel and organic matter deposited in river channels and associated floodplains. The Law Sand and Gravel Member includes recent (currently accumulating) river deposits in the upper Clyde valley and deposits associated with the rivers Kelvin and the Black and White Cart Waters. Small alluvial fans and deposits associated with minor streams are also included in this unit.

2.10 LACUSTRINE DEPOSITS (LDE)

Recent lacustrine deposits, consisting largely of soft silt and clay with organic bands and lenses of peat, are found in and around lakes or former lakes throughout the Clyde area. These lakes have formed in inter-drumlin hollows, and some have been completely infilled by accumulation of sediment and organic matter.

2.11 PEAT

Small deposits of peat, consisting of dark, organic rich, humic material formed by the accumulation of partially decomposed vegetation, are found in places in the Clyde area. Peat accumulations are generally associated with lacustrine and alluvial sediments, where they may form surface deposits, or form bands or lenses within the strata (discussed below).

2.12 HEAD

Small areas of gravely clay overlying the Bridgeton Sand Formation, Law Sand and Gravel Member or the Paisley Clay Member, usually found at the base of a drumlin with significant relief, are interpreted as Head deposits formed by the remobilisation of the surface deposits on steep hillslopes

2.13 MADE GROUND (MGR)

Made ground in the 3D model represents a combination of made and worked ground including filled and partially back-filled pits and quarries - hence it comprises all anthropogenic deposits. Areas of worked ground were primarily identified using DiGMapGB 1:10 000 polygons. These were subsequently altered to encompass areas where boreholes reported additional areas of artificial ground. Alterations were made using the Ordnance Survey maps to identify the extent of industrial areas, housing developments and other information. It is likely that more extensive but thinner deposits of made ground occur within the model that are not currently represented. This is particularly the case on sheet NS56NE (Kelvinside-Springburn and surrounds). Made ground has not been subdivided.

An accurate 5 m DTM and good quality borehole descriptions would be essential to the more detailed modelling of the made ground in the Clyde Valley area. Subdivision of the made ground will be considered in future models.

2.14 LENSES

Many of the units described above contain considerable variation in lithologies within their strata. Where thin deposits of a contrasting lithology to the main unit are recorded within borehole descriptions, these have been depicted by the modelling of a lense contained within the 'parent' unit. In general, only lithological sub-units with thicknesses greater than approximately 2 m have been identified as separate lenses.

The lense types used in the Superficial Deposits Models are: clay_lense, silt_lense, sand_lense, gravel_lense, peat_lense, till_lense, CADR_lense, CADR2_lense, Witi_lense (Boulder clay without the clay fraction (washed out)).

CLAY AND SILT		SAND AND GRAVEL		DIAMICTON	PEAT	LITHOLOGY
Marine	Lac/Fluv	Marine	Lac/Fluv	Glacial	Organic	ORIGIN
		Gourock	Law		Clippens	FLANDRIAN
		Killearn				DEVENSIAN
Paisley						
		Bridgeton				
	Bellshill					
			Ross			
			Broomhouse			
				Wilderness		
			Cadder			

Table 2 Summary of origin of superficial deposits stratigraphic units in the Central Glasgow area: lithology, origin and age (Lac – lacustrine, Fluv – fluvial).

2.15 BEDROCK

The bedrock geology beneath the Bedrock Model area comprises Upper Carboniferous Coal Measures, Clackmannan and Strathclyde group strata (Table 3, Figure 3). The majority of the strata represent fluvio-deltaic to shallow marine facies consisting of argillaceous rock, sandstone, coal and limestone. The lithostratigraphy is primarily identified from interpretation of borehole records using the established BGS Carboniferous lithostratigraphic framework, lithostratigraphic and biostratigraphic markers (Browne et al., 1999; Hall et al., 1998).

Modelled horizon – Central Glasgow bedrock model	**Rock volume above modelled horizon to next modelled horizon**	**Modelled horizon – Clyde Catchment scale bedrock model**	**Rock volume above modelled horizon to next modelled horizon**
Rockhead unconformity from superficial deposits modelling (Combined base of all the superficial deposits)		Rockhead unconformity from BGS rockhead model (regional)	
Base Upper Coal Measures bUCMS (UCMS-CYCCM)	UCMS- CYCCM		
Glasgow Upper coal (GU-COAL) Worked coal in Scottish Middle Coal Measures Formation (MCMS)	MCMS- CYCCM		
Glasgow Ell Coal (GE-COAL) Worked coal in Scottish Middle Coal Measures Formation (MCMS)	MCMS- CYCCM	Glasgow Ell Coal (GE-COAL)	MCMS-CYCCM and UCMS- CYCCM
Kiltongue Coal (KILC_COAL) Worked coal in Scottish Lower Coal Measures Formation (LCMS)	MCMS-CYCCM and LCMS- CYCCM		
		Base Lower Coal Measures Scotland (LCMS-CYCCM) = base Coal Measures Group Scotland (CMSC) bCMSC	MCMS-CYCCM and LCMS-CYCCM
Base Upper Limestone Formation bULGS (ULGS-CYCC) = Index Limestone (ILS-LMST)	LCMS-CYCCM and PGP-CYCC and ULGS-CYCC	Base Upper Limestone Formation bULGS (ULGS-CYCC) = Index Limestone (ILS-LMST)	PGP-CYCC and ULGS-CYCC
Knightswood Gas Coal (KDG_COAL) Worked coal in Limestone Coal Formation (LSC)	LSC- CYCC		
		Base Lower Limestone Formation bLLGS (LLGS-CYCC)= Hurlet Limestone HUR-LMST	LSC-CYCC and LLGS-CYCC

Table 3 Summary of modelled bedrock surfaces in the two models including stratigraphic and rock type codes of the intervening volumes.

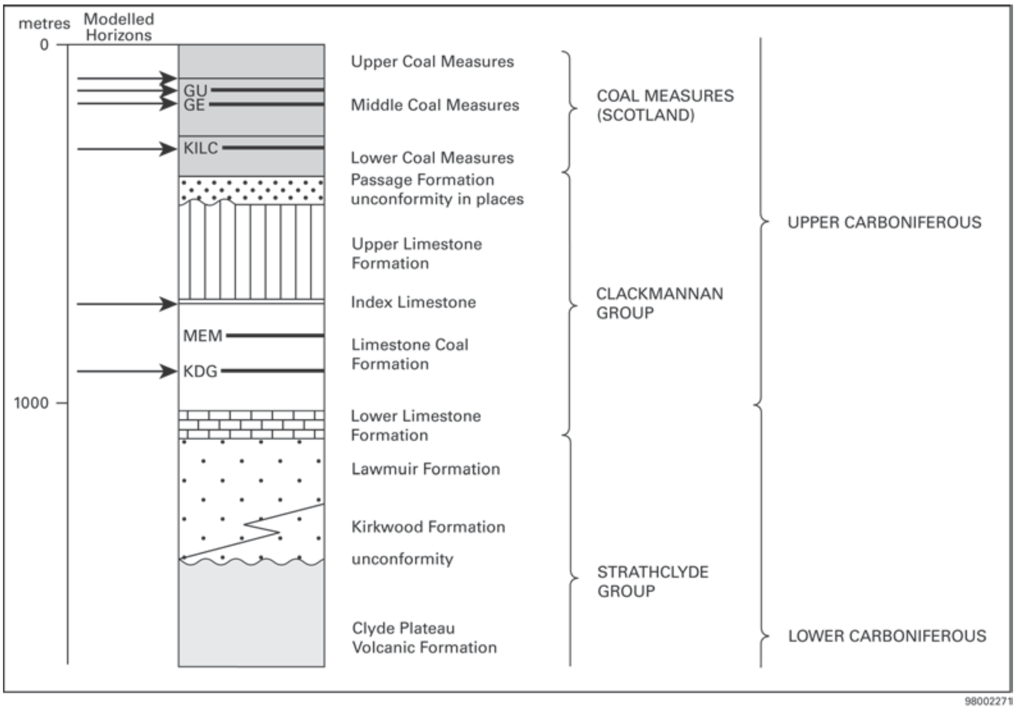

Figure 3 Summary stratigraphy of the modelled Carboniferous strata in the Central Glasgow bedrock model area. Coal name codes: Glasgow Upper coal (GU), Glasgow Ell Coal (GE), Kiltongue Coal (KILC), Knightswood Gas Coal (KDG). The base of the Lower Limestone Formation (Hurlet Limestone) is also included in the Clyde Catchment scale bedrock model

GU and GE are the uppermost and most extensively worked coals in the Scottish Middle Coal Measures Formation (MCMS) in the Central Glasgow area. KILC is quite extensively worked in the Scottish Lower Coal Measures Formation (LCMS). KDG is extensively worked within the Limestone Coal Formation, cropping out on the western side of the Central Glasgow area.

3 Modelled faults

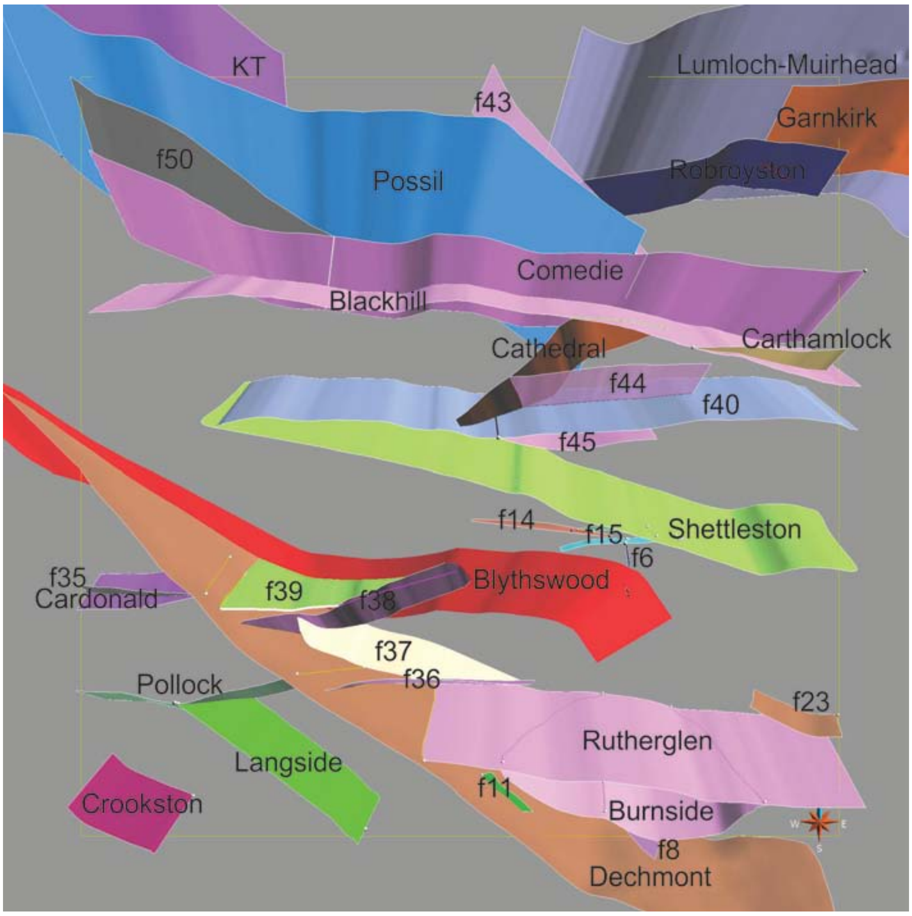

Figure 4 Overview of faults modelled in the Central Glasgow bedrock model, looking from above.

Dipping faults were included in the Central Glasgow bedrock model (Figure 4). Some faults have long-established names, while others are designated informally (e.g. f23). With a few exceptions relating to the inclusion of smaller structures on NS66SW, faults were included in the model if over 30 m throw or 2 km in length.

In the Central Glasgow bedrock model, fault dips were calculated where data were available using the XYZ positions recorded in subsurface mine abandonment plans and linked to the surface outcrop position. The data were mainly available on NS66SW, showing that the majority of faults have dips of c. 60°. One fault, the Burnside Fault (Figure 4), has a c. 45° dip. Occasionally, fault information was encountered in boreholes. However, the amount of fault subsurface position information from mining and boreholes is generally very limited (and not enough to make a fault defining pointset). Thus, faults were created by projection from their mapped outcrop position at 60° (apart from Burnside at 45°).

The availability of mining information on NS66SW meant that faults could be analysed for their continuation at depth. Smaller faults were observed to terminate within 100 m of rockhead (e.g. F6, Figure 4) whereas larger structures (e.g. Rutherglen) extend to the depth of the whole of the model. On NS66NW and NS56SE, mining information was more limited and faults incorporated in the model were generally larger in terms of length (and therefore probably depth also), such that faults on these sheets were extended to a standard depth of 1 km.

Only faults with larger throws of greater than tens of metres and lengths of kilometres were included in the Clyde Catchment scale bedrock model. Generally the modelled position of faults is consistent between the two models, though two faults have a differing dip in the Clyde

Catchment bedrock model due to evidence available outside the Central Glasgow area. In the buffer zone provided to the ASK Network there are over 100 parts of modelled faults.

4 Model datasets and workflow

General caveats regarding BGS datasets and interpretations can be described:

- Geological observations and interpretations are made according to the prevailing understanding of the subject at the time. The quality of such observations and interpretations may be affected by the availability of new data, by subsequent advances in knowledge, improved methods of interpretation, improved databases and modelling software, and better access to sampling locations.
- Raw data may have been transcribed from analogue to digital format, or may have been acquired by means of automated measuring techniques. Although such processes are subjected to quality control to ensure reliability where possible, some raw data may have been processed without human intervention and may in consequence contain undetected errors.

4.1 SUPERFICIAL DEPOSITS

The Superficial Deposits models were constructed in GSI3D using a NEXTMap® Digital Elevation Model ©Intermap Technologies, at 50 m resolution (Central Glasgow, North Glasgow, South Glasgow) or 25 m resolution (Paisley, Clydebank), the BGS digital borehole database, BGS 1:10 000 scale digital maps (DiGMapGB, 2009), BGS 1:50 000 maps (DiGMapGB, 2008), field slip scans, historic maps and scanned geological cross-sections. Other literature such as BGS regional geological guides and scientific papers influenced the correlation of geological units.

Borehole data were entered to the BGS corporate database BGS Borehole Geology. The spread of borehole data across the area was variable, from extremely closely spaced at site investigation locations to more widely spaced and isolated boreholes.

A standard GSI3D workflow for superficial geological models was followed (Kessler et al., 2008 http://nora.nerc.ac.uk/3737/1/OR08001.pdf) for the original component block models. The method principally involves construction of cross-sections between the best quality borehole data followed by envelope construction around the limits of the geological units. GSI3D model calculation then uses envelopes in combination with nodes on the geological surfaces along cross-sections to build geological surfaces by triangulation.

The original component block models (Figure 1) and individual map sheets within the block models were modelled over a number of years, by a number of geologists and during a period of software development. As such, a number of steps were taken before release of these v2 (or v3 Central Glasgow) models to attempt to resolve inconsistencies between block models. Further details are documented in Whitbread (2013). The key steps included:

1. Inclusion/exclusion of water bodies to a common standard (see section 5.1.1 below)
2. Creation of a set of merged borehole data for each component block model
3. Creation of a set of master envelopes ‘extents’ covering the modelled area
4. Inclusion of higher resolution corridor model sections and envelope edits on SW Central Glasgow and Paisley (Monaghan and Whitbread, 2012)
5. Revision to Lexicon and lithology codes describing the modelled units to current best practice and update GVS, legend and GSIPR files
6. Using extended DTM’s to cover the edge matching zone for each model

7. Edge matching the block models such that the geological interpretation was consistent across block boundaries. The main issues to be resolved were
    a. Marine-influenced Gourock Sand Member (GOSA) has been modelled flanking the Clyde in Clydebank and Central Glasgow, but the equivalent unit is modelled as fluvial Law Sand and Gravel Member (LAW) to the south-east of Glasgow, upstream of the tidal limit. This was resolved by taking the GOSA as far as the Uddingston-Bothwell area and then using the LAW upstream of this.
    b. The Paisley Clay Member was not modelled under Linwood Clay Member in the north-west quarter sheet of Paisley Model meaning that the Paisley Clay in the Clydebank Model ended abruptly at the model edge. Conversely the Linwood Clay was not modelled in the north-east of the Paisley Model. This was resolved by undertaking a revised interpretation of both units on both block models, such that they are now consistent.
    c. Edge matching issues in envelopes (XY) or sections (Z) viewed as linear jumps. These were resolved by revised interpretations, guided by borehole data in the problem areas.

The following inconsistencies were not attempted to be resolved at this stage:

- Insertion of additional cross-sections to achieve a more uniform cross-section coverage
- Revision of made ground (particularly on NS56NE) where some boreholes prove made ground that is not modelled.

4.2 BEDROCK

The Central Glasgow and Clyde Catchment scale bedrock models were constructed from all borehole data entered to the BGS corporate database BGS_ Borehole_Geology and reaching the modelled horizons, and mine plan, map outcrop and interpreted data.

The spread of borehole data across the area was very variable, from closely-spaced site investigations metres apart, to in extreme cases, boreholes more than a kilometre apart. Data points were concentrated around the outcrop of worked coals and were sparse on stratigraphic surfaces in deeper parts of the basin.

Most borehole data points have a reasonably good level of certainty. Boreholes with very poor quality records or very poorly known sites were not coded into the database. However, there can be uncertainty: in geologically coding short isolated site investigation boreholes; in a drillers record of a borehole (i.e. if not examined by a geologist); or sometimes in the siting of the borehole. However, these should result in errors in location being no greater than about 5–10 m in Z, and perhaps 20–50 m in terms of XY.

Mining data were compiled from all available mine abandonment plans. These consist of spot heights surveyed on the base of worked coal seams underground, and rarely of structure contour elevation data. The distribution of mining data points is variable. These data points have a high confidence level as they were systematically surveyed. Estimates of error on mining data points range from 0–5 m in Z and 0–25 m in XY.

The bedrock map represents the outcrop (or subcrop) of stratigraphic horizons at rockhead i.e. very commonly buried beneath superficial deposits. For the Central Glasgow bedrock model, the map data for NS66SW had been revised prior to this study and an updated map published (BGS, 2008). The map data for NS56SE and NS66NW were revised prior to the study but those revisions have not been published. That is the model contains more up-to-date map linework than does the current edition of the 1:10 000-scale maps (BGS, 1995, 1996). The errors in mapped outcrop line work are extremely variable – from 0–10 m in XYZ where seen at outcrop, to tens of metres where an interpretive outcrop was created from little constraining data.

For the Clyde Catchment scale bedrock model a variety of map scales have been used to constrain the modelled extent. 1:10 000 scale data was used for the Glasgow Ell Coal seam whereas 1: 50 000 and smaller scale data has been used for the stratigraphic horizons (McCormac, 2013). For all modelled horizons the outcrop extent has been simplified to be appropriate for the scale and resolution of the regional scale of the model.

A standard BGS GOCAD® modelling workflow using the structural workflow was employed. GOCAD® (Paradigm, www.pdgm.com) calculates a triangulated mesh based on XYZ data points and then the geologist modeller undertakes various processes to aid geological interpretation in data poor areas. Expert geological interpretation was added during modelling as cross-sections, isopach maps, editing of fault-surface contacts and removal of overlaps during GOCAD® modelling.

5 Model assumptions, geological rules used

5.1 SUPERFICIAL DEPOSITS

Where no boreholes were present, basal units were modelled to the BGS rockhead model (see http://www.bgs.ac.uk/products/onshore/superficialThickness.html). Where the depth of rockhead in boreholes differed from the rockhead model, the borehole depth was preferred.

5.1.1 Water modelling

A consistent approach to the modelling of water was attempted across all the modelled blocks shown on Figure 1. Firstly, a water envelope (extent) was extracted from the OS 1:10 000 scale Open data digital map. Judgement was then used to extract a subset of the larger water bodies from that map data such that the River Clyde, the lower parts of the White Cart and Black Cart waters and lakes/reservoirs exceeding approximately 150 m in width/length are included in the 3D model.

During modelling, the water bodies were generally fitted to the water envelope and not to the DTM as it is assumed that users will wish to attach the model to an OS map base rather than a derived/simplified NextMap DTM. The result is that in a few places where the DTM and OS map data do not match, water appears as if it goes uphill. In places (e.g. Balgray reservoir) other artefacts exist within the modelled water (e.g. where there is a bridge over the reservoir the DTM/water volume is raised up as the bridge is not modelled as such). In some areas there is made ground beneath water at dams, or along tidal parts of the River Clyde. The OS Open data envelope (extent) for water which extended to high water mark *was* edited within the intertidal zone in the Clydebank and western Central Glasgow models such that it fitted the NEXTmap® DTM in which ocean surface is levelled to OSGB1936 geodetic datum (i.e.zero metres relative to OD, or low water mark).

The depth of water within the tidal limit of the River Clyde was based approximately on a UK Hydrographic Office Admiralty Chart (International Chart Series c.2000). Where no information is available a sub-rectangular river channel cross-section has been assumed.

The depth of reservoirs was unknown and so they were modelled to water depth of about 10 m.

5.2 BEDROCK

It is assumed that all data types (borehole, mine plan, map) are included with equal weight in the modelled surface calculation, though in reality some data may be more certain than others. Data points were excluded if clearly erroneous, based on the geologist's judgement.

6 Model limitations

6.1 SUPERFICIAL DEPOSITS

General

- Best endeavours (quality checking procedures) were 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 location).
- The model does not reflect the full complexity of the superficial deposits geology. In reality, surfaces have been subjected to more glacitectonic deformation than is represented in the model. It is also known that made, worked and artificial ground is more widespread than is shown by the model (e.g on NS56NE as proven by boreholes), and could be subdivided into more detail than the 'made ground' currently used.
- Smaller rivers, streams and water bodies have not been included in the models (see section 5.1.1)
- The model is attributed with geotechnical and hydrogeological properties – these can be seen in the Lithoframe Viewer. These are simply bulk attributions based on point data in boreholes from Central Glasgow and are provided for general guidance only.
- The cross-section density and therefore model certainty is variable across the model, and is based on complexity and type of geology, borehole density etc.

DTM

- The NEXTMap® Digital Elevation Model was subsampled from a 5 m resolution to 50 m or 25 m resolution which means the surface distribution and geometry of a geological unit does not reflect the highest resolution possible. This resolution was chosen based on the size of the area, the resolution of the original modelling and the software capability. Some minor mismatches between geomorphological features and modelled units (including water) and the DTM occur due to the coarse resolution of the DTM.
- The NEXTMap® Digital Elevation Model may contain artefacts such as trees or artificial structures such as pylons. The majority of these have been stripped out before modelling. If any of these artefacts were found during the modelling then the effects of these were minimised in the model as much as possible.

Borehole data

- The start heights of boreholes used might differ significantly from the NEXTMap® Digital Elevation Model. When modelling, these differences were taken account of by assessing the year the borehole was drilled and assessing the location of the borehole against other data such as historical maps. Therefore the modeller used their own judgment in some areas if the stratigraphy in the borehole did not match the modern day topography and changes in the subsurface (quarrying, landfill etc).

- A subset of the most reliable borehole data has been included to constrain the cross-sections within the model. However there is also a large subset of borehole data that has not been included within the model (see section 8 below).

Map data

- In the absence of borehole information, the model is constrained by map data and the DTM. Modelling highlights areas where the geological map may need revision, but this was not undertaken as part of the modelling exercise. The most common areas requiring revision relate to anthropogenic activity post-mapping (e.g. worked/made ground).
- Small parts of unit extents (envelopes) constraining the modelled volumes are relatively straight-edged in a limited number of cases e.g. witi-dmtn in the northern part of Clydebank, pais-xczs in eastern parts of Paisley, which is not geologically realistic and should be improved by future work.
- The south-east central part of the Paisley model (northern part of sheet NS55NW) incorporates some inconsistencies of up to 20 m between 1:10,000 scale artificial ground and 1:50,000 scale superficial deposits DigMapGB map data. The made ground in this area has been selectively extended to match the superficial deposits based on 1:50,000 scale DigMapGB data (BGS, 2008).

Modelled surfaces and volumes

- The thin nature of made ground, and the thin draped form of some areas e.g. Paisley Clay Member deposits, means that these units are poorly shown in visualisations of the 3D model (e.g. in the Lithoframe Viewer 3D window). A substantial number of additional cross-sections (‘helper sections’) are needed to improve the calculation of thin deposits.
- A known limitation is that for some thin units close to DTM surface and over topographically variable ground (water, MGR, LDE, LAW, KELV, KARN, BILL1, WITI), the superficial deposits ASCII and ESRI grids contain small patches of no modelled surface within the unit envelope (outline, supplied as an ESRI shapefile) where it should exist. The limitation is greatest in the southern Paisley and South Glasgow block models, where topography is greatest, and the largest area affected is a maximum of 600 by 400 m. This artefact of the modelling software/procedure can be rectified with additional interpreted cross-sections or improved meshing algorithms and will be addressed in future work.
- The modelled volumes (visible in the Lithoframe Viewer 3D window) representing some elongate units such as water, made ground along road or rail embankments and alluvium are in places spiky/angular due to a combination of steep edges, DTM resolution and limited constraining cross-sections. However, the size of the angularity is in proportion to the unit and is accepted as a known limitation. Quality control by visual inspection identified additional local high or low areas (lumps or spikes) in the modelled volume. The majority of these are intentional as they result from borehole interpretation in constraining cross-sections.
- Whilst effort has been put into making models consistent and edge matched there remain minor inconsistencies between models produced and calculated separately along 5 km grid square boundaries (e.g. NS56SE/NS66SW in the vicinity of the River Clyde) and small variations in interpretive style from different modelling geologists. These

inconsistencies should not be apparent unless the models are being used at high resolution.

6.2 BEDROCK

General

- The model does not reflect the full complexity of the geology. In reality, geological surfaces will be cut with igneous intrusions/vents and cut by more faults than are modelled.
- The GOCAD® algorithm creates a triangular mesh to try and best fit all data points. For the Central Glasgow bedrock model a mesh size of around 120 m was optimal, as there are large areas without any data points. A smaller mesh size was tested but the resultant surfaces did not appear geologically realistic. In areas where there are abundant closely-spaced data (e.g. site investigations, or at a complex part of the outcrop line) a 100–200 m mesh size cannot represent the detail of the data density and complexity. In summary, the meshes are a representation of the geology, using all the data but not fitting all of it exactly. The maximum deviation between a surface and a data point is about 20 m. In the majority of cases the difference between any known data point and the modelled surface is less than 5 m.
- For the Clyde Catchment scale bedrock model, the model mesh size was between 100 to 500 m.
- All data points have been checked on data entry and for consistency in the model but there will be some errors that remain – for example boreholes whose site has been incorrectly located in the database, or whose recorded start height is wrong.
- Note that to load to ArcGIS®, the modelled TIN (triangular mesh) files have been converted to ASCII grids. A grid spacing of 25 m (Central Glasgow) or 50 m (Clyde Catchment scale bedrock model) was used so that some detail of fault gaps is preserved. This may give a false impression of the model resolution as the original TIN mesh spacing was 100–200 m. The ArcGIS® grids do not give a clean/fitted together 3D model (e.g. at fault-surface contacts) because of the TIN to grid conversion process.

Faults

- Faults with offsets less than 30 m have not been included in the Central Glasgow bedrock model because the data were insufficient to constrain them. There will be some areas where adjacent data points have significantly different Z values because they are offset by a fault that is not modelled. For the Clyde Catchment scale bedrock model, faults with offsets less than tens of metres were not included.
- Fault geometries which terminate against each other at low angles result in numerous thin ‘slivers’. These are difficult to model satisfactorily and are often poorly constrained by data (e.g. at junction of Blythswood, f38 and f39 in the Central Glasgow bedrock model). There is a small sliver of the Kiltongue Coal surface that penetrates through f38, and should not. Thus thin slivers should be treated as parts of the model with high uncertainty.
- In the Central Glasgow bedrock model f40 reverses throw along its length, as on the 10 000 scale map, but the fault dip has consistently been modelled at 60° to the north along the whole structure.

- In the Central Glasgow bedrock model the scale of faults modelled is inconsistent. Some smaller faults have been included (f14,15,6) where they constrain the outcrop of the modelled coals on NS66SW. In other areas of the model, only much larger fault structures have been included. Known, smaller faults have been excluded.

Surfaces

- A more recent and higher resolution model along a linear corridor covering the southwestern part of the Central Glasgow bedrock model (Monaghan, 2012b) has highlighted that the KILC, bULGS, KDG modelled surfaces are too high in the Central Glasgow Bedrock Model where they are interpreted in the hangingwall (eastern side) of the Dechmont fault.
- The two models supplied are suitable for use at different scales – Central Glasgow bedrock at 1:10 000 to 1:50 000 versus the Clyde Catchment scale bedrock model at 1:100 000 to 1:250 000. The models are not edge matched along their boundary.
- Smaller ‘ holes’ in the modelled surface have not been cut in the Clyde Catchment scale bedrock model (e.g. noticeable at the edge join of the Central Glasgow and Clyde Catchment scale bedrock models on the Glasgow Ell surface).
- In the Central Glasgow bedrock model isopach maps and cross-sections through the stacked surfaces and faults highlight inconsistencies caused by lack of data, particularly on the more deeply buried parts of KDG and Base ULGS/ILS, or by patchy data coverage on one particular surface (e.g. circular inconsistencies caused by data on a particular coal seam from a particular, localised set of boreholes between GU and GE). For example, the variation in general dip between faults 37 and 38 on KILC-ILS-KDG surfaces is inconsistent. Generally the KDG and ILS modelled surfaces are much more uncertain away from their outcrop than the other modelled surfaces, due to lack of data.
- Very small areas of bedrock surfaces lie up to 2 metres higher than the rockhead model causing a local crossover. This happens in areas where there are local low points in the higher resolution mesh of the rockhead surface, and there are no TIN points within that area from the lower resolution bedrock mesh (crossovers at TIN points should have been removed).

7 Model images

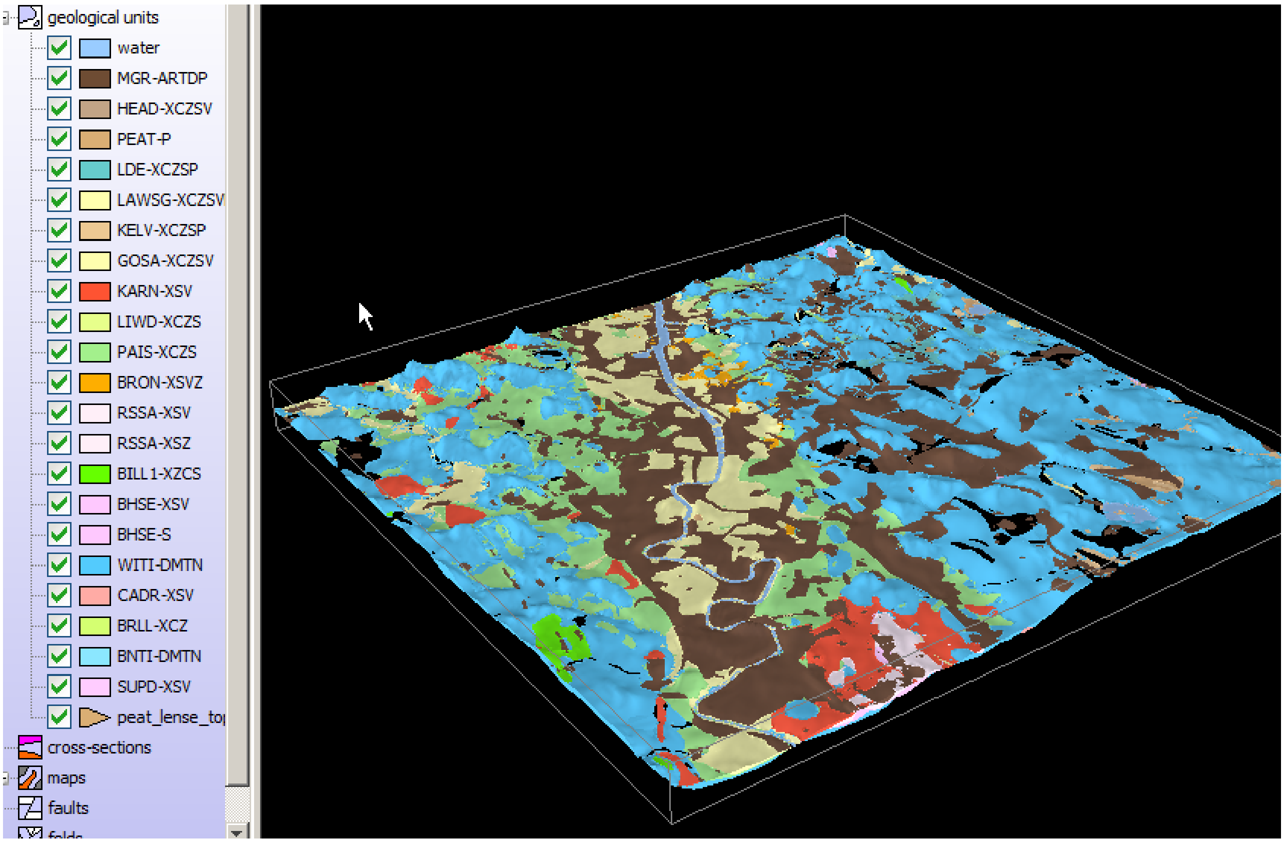

Figure 5 Overview of superficial deposits model of Central Glasgow Superficial Deposits Model, looking NW, ten times vertical exaggeration.

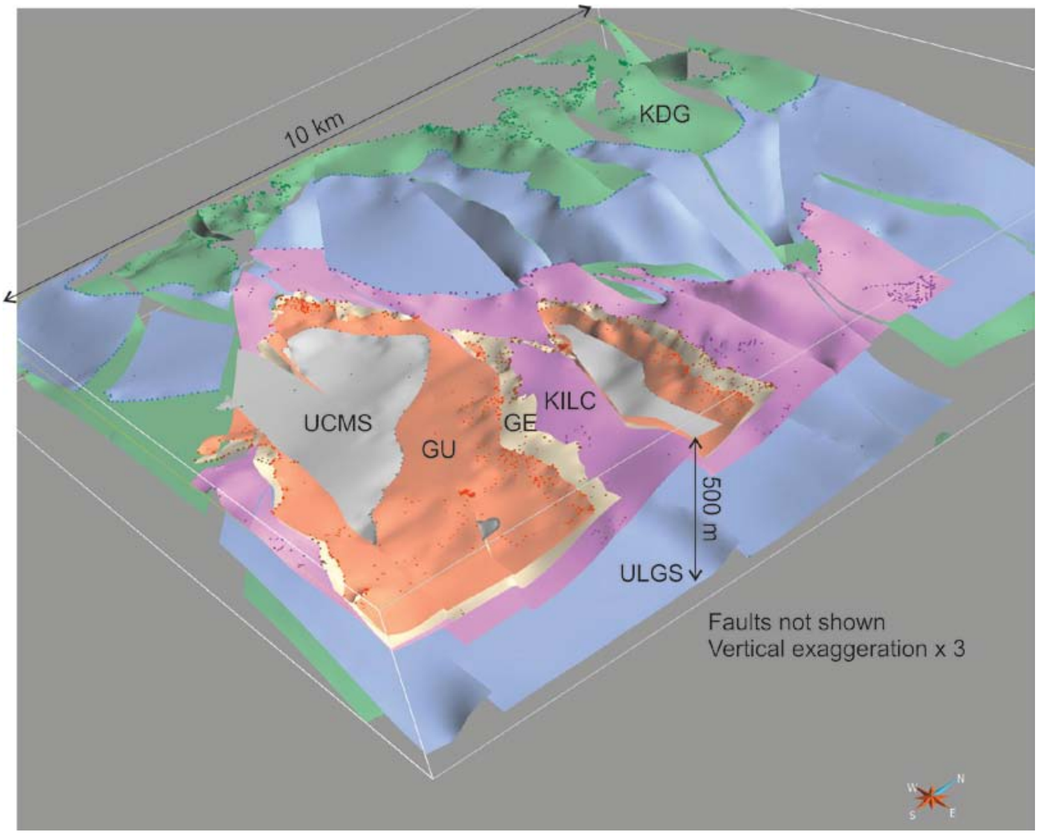

Figure 6 Overview of bedrock surfaces modelled in the Central Glasgow Bedrock Model with data points from boreholes, mine plans and mapped outcrop shown.

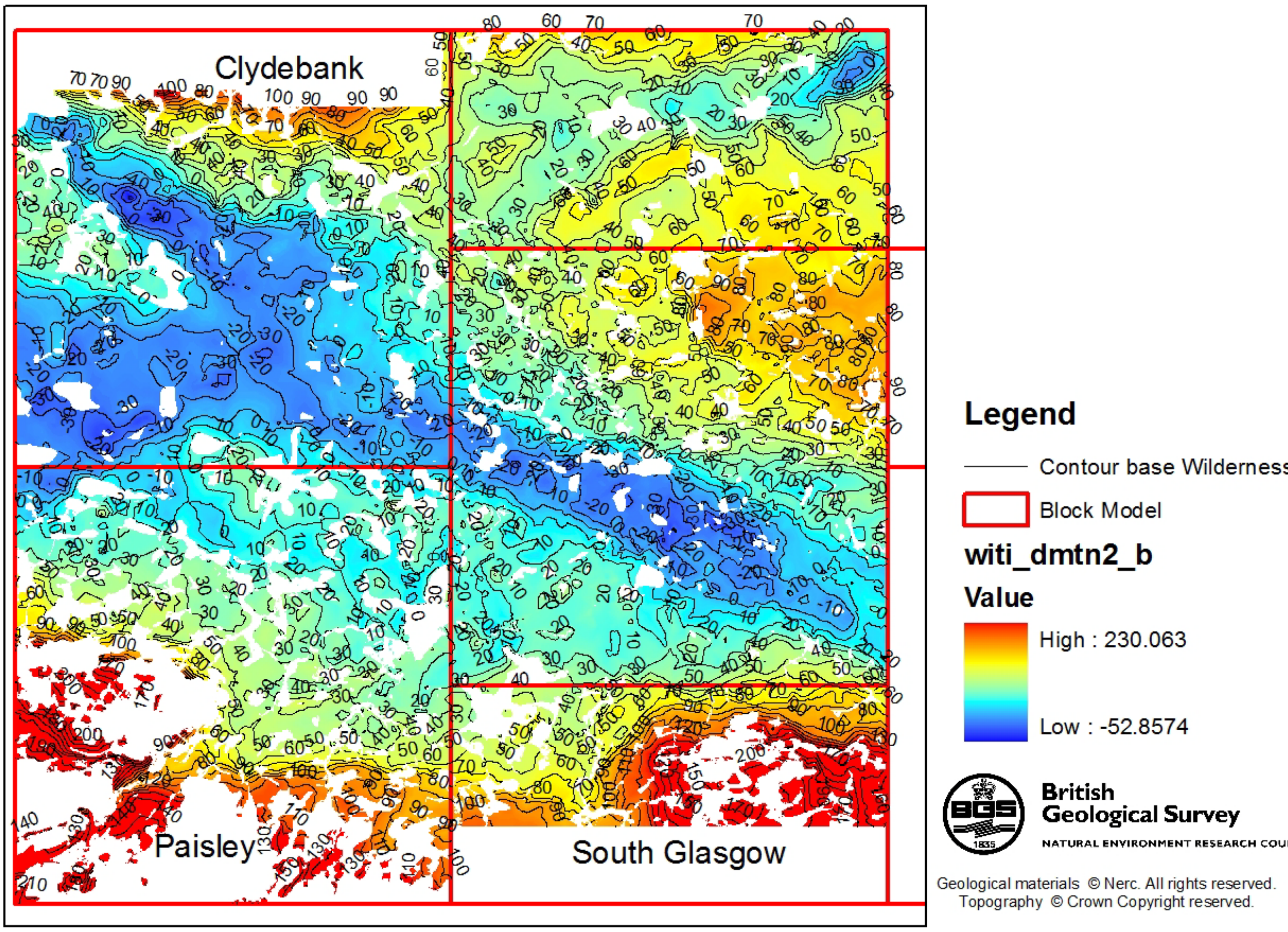

Figure 7 Contoured map (metres relative to OD) on the base of the modelled Wilderness Till Formation across the 5 block models released to the ASK Network in June 2013.

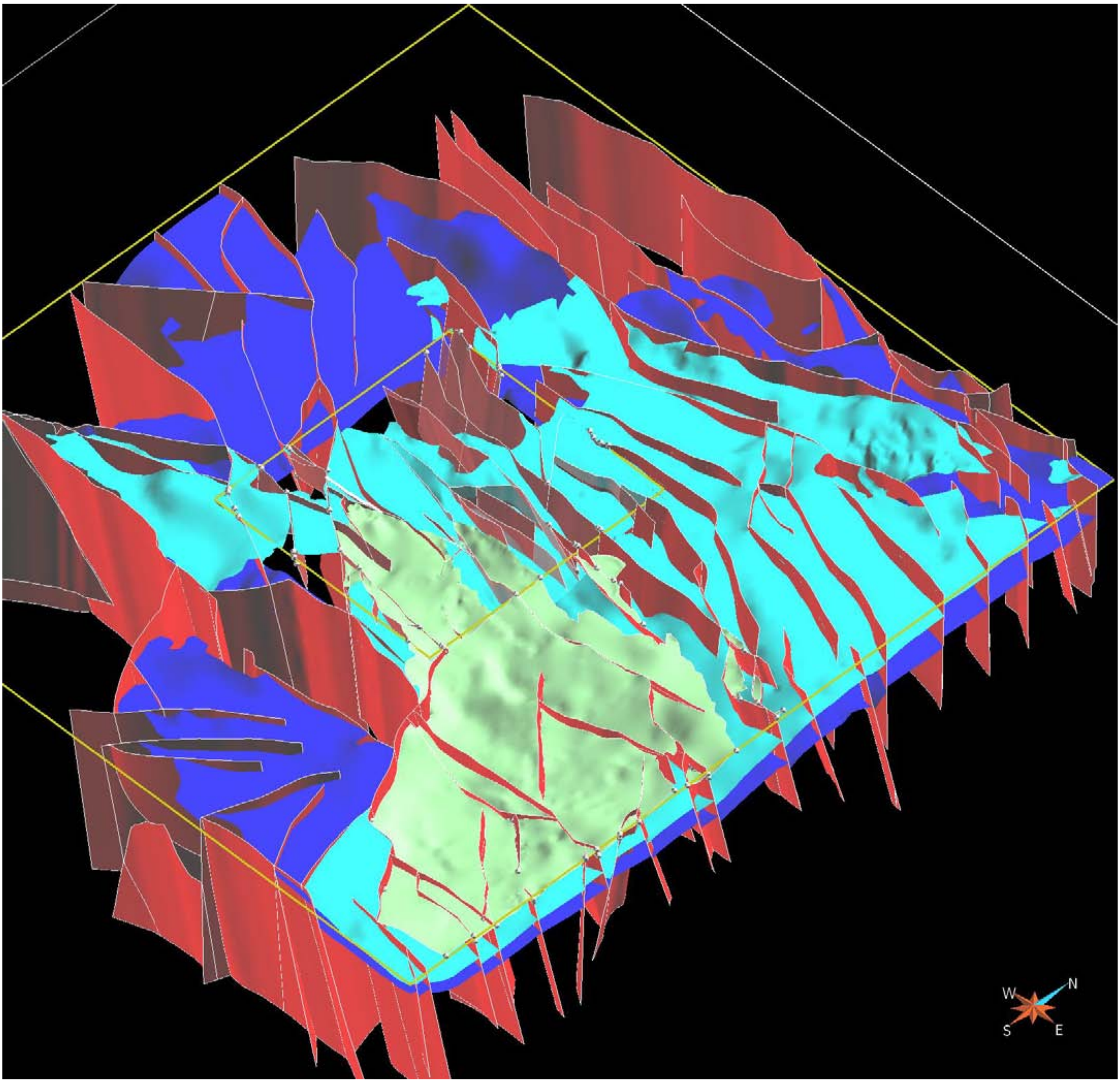

Figure 8 Image of the Central Glasgow and Clyde Catchment faulted bedrock models, looking north-west, vertical exaggeration x 3, GE=green, bULGS=pale blue, BLLGS= dark blue, faults in red. 10 km buffer zone and area of Central Glasgow bedrock model in yellow.

8 Model uncertainty

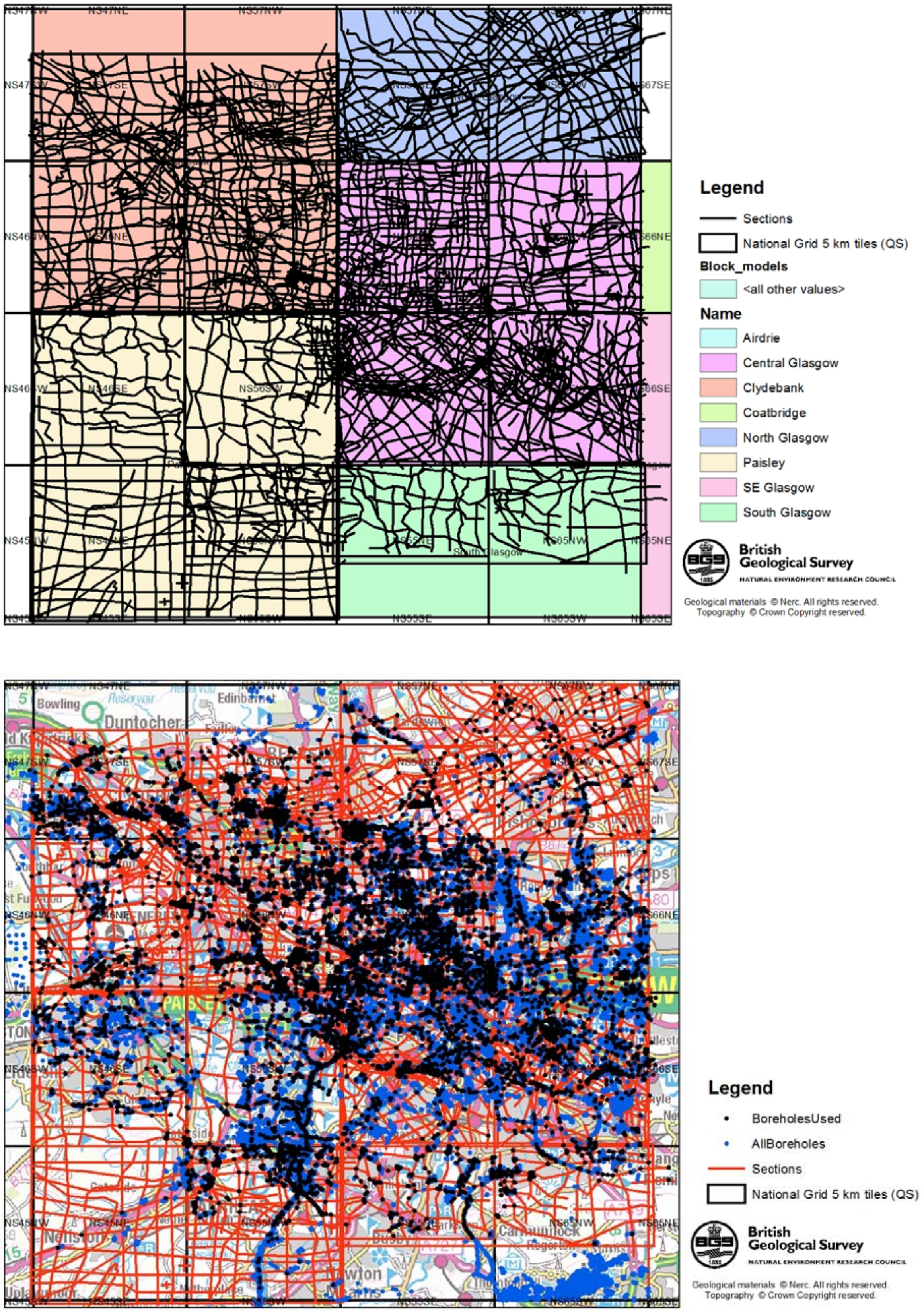

Figure 9 a) Array of cross-section lines used to constrain the five superficial deposits models. b) Cross-section array with boreholes used in the modelling, and all boreholes shown.

The cross-sections and borehole data points constraining the Superficial Deposits Models shown in Figure 9 give an indication of the most certain areas of the model containing the most sections and borehole data (e.g. Central Glasgow superficial deposits model), and the least certain areas (southwest of Paisley model, South and North Glasgow superficial deposits models). Note also on Figure 9 the extent of the Clydebank and South Glasgow models, which do not cover the whole map sheet. A more quantitative approach (described below) is also used in BGS to indicate model uncertainty. In due course, uncertainty layers will be calculated for the whole area of the superficial deposits models.

Currently, ASK Network users are supplied with uncertainty layers from an earlier (2009) version of the 3D geological model for evaluation purposes. The uncertainty layers cover 3 quarter sheets of the Central Glasgow models (NS66SW, NS66NW and NS56SE). Comments on the utility of these uncertainty layers would be welcomed.

The uncertainty layers are supplied in two formats (1) .jpg with .jgw raster image files and (2) ASC files, which can be converted to ArcGIS® grids, for example, using ArcToolBox (‘conversion tools’ –‘ASCII to raster’). When viewing the converted ASC files, the user needs to colour up the grids based on the ‘count’ field, which is the relative value of uncertainty for that layer of the model. The largest number represents relative high uncertainty and the smallest number represents relative low uncertainty.

Uncertainty layers were calculated from a combination of data density and geological complexity of the modelled surface. The BGS confidence calculator v1_2 - customised BGS software developed in Matlab - was used. This means the model will be most uncertain where there is little data and where the geological surface dip changes rapidly.

For the superficial deposits model, relative low uncertainty might be considered to have errors of the order of ± 10 m in XYZ, for example, those areas coloured green on Figure 10. In the most uncertain areas where the geology is complex and poorly constrained by borehole data, uncertainty may be approximately ± 70 m in XYZ for example, those areas coloured red on Figure 10.

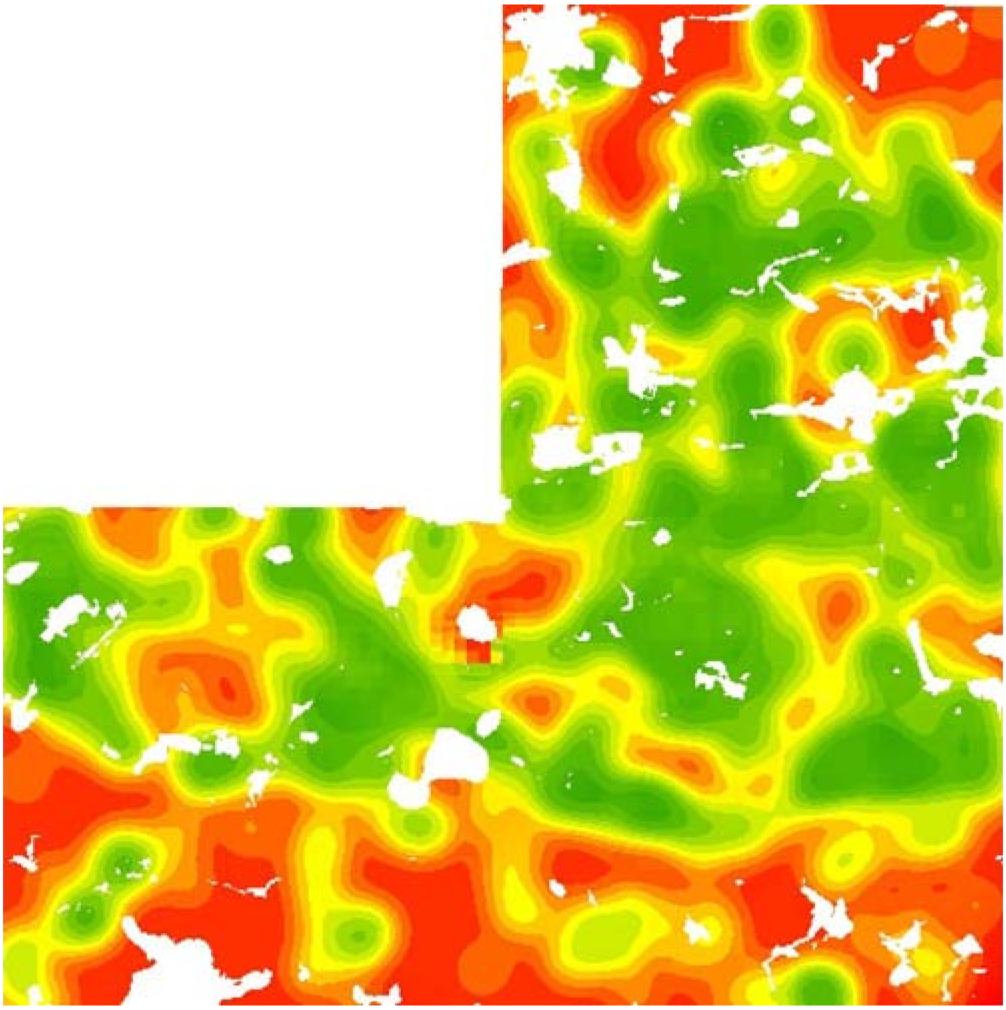

Figure 10 Uncertainty layer for the Wilderness Till coloured up such that the relatively most uncertain areas are red, relatively least uncertain areas are green (covers NS66SW, NS66NW and NS56SE).

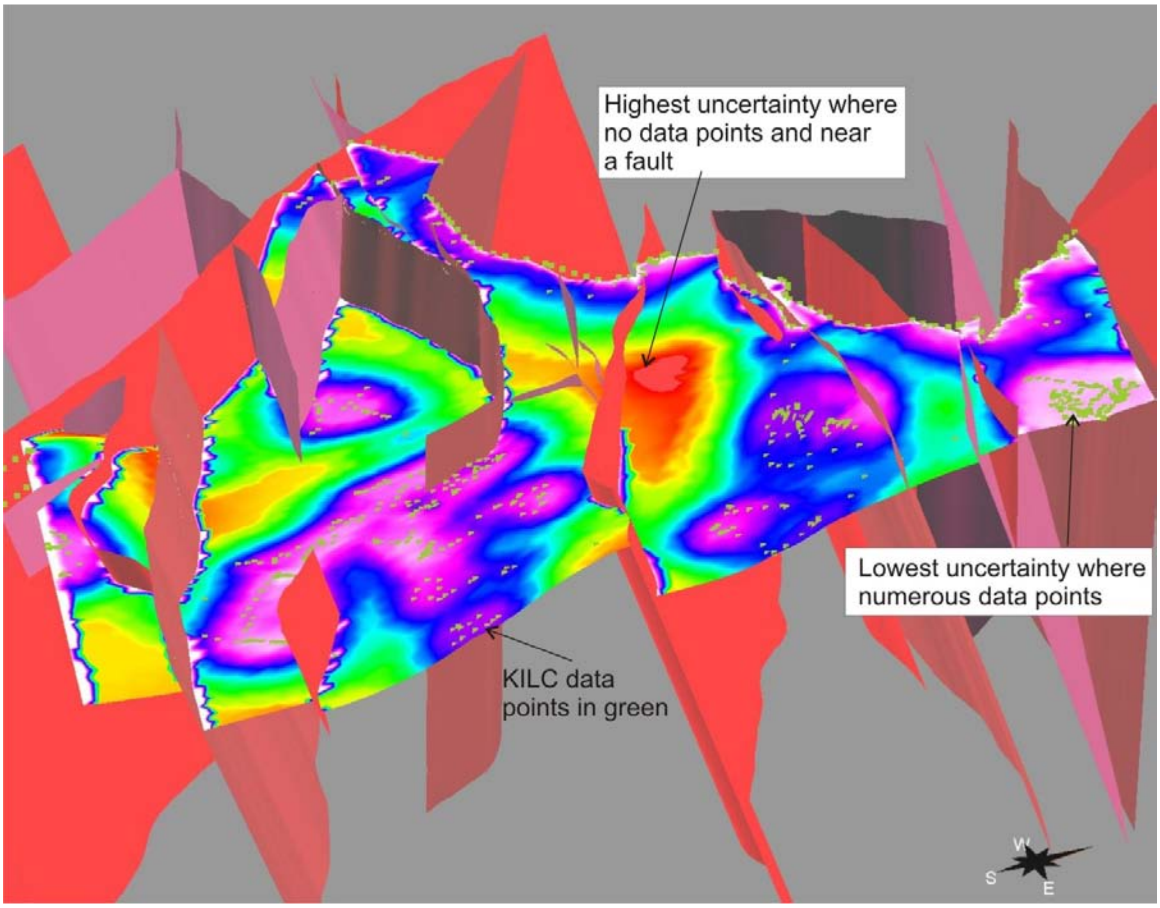

Figure 11 Example of combined uncertainty attribute for KILC draped on the geological surface in GOCAD®

For the bedrock surfaces, lowest uncertainty (highest confidence) areas are those that are well constrained by geological data and where the geology is relatively simple. In these areas, the error on the model might be considered to be of the order of ± 10 m in XYZ; for example, those areas of the KILC uncertainty surface on Figure 11 that are purple or pink.

Highest uncertainty (lowest confidence) areas are areas that are not constrained by any geological data and where the geology is complex i.e. faulted or folded. In these areas, the error on the model might be considered to be of the order of ± 70 m in XYZ; for example those areas of the KILC uncertainty surface on Figure 11 that are orange or red.

9 Conclusions and potential future developments

Comments and feedback on the geological models are encouraged from ASK network members.

Improvements could be made to the Superficial Deposits Models by inclusion of more borehole data, increased section density, and improved artificial ground modelling.

Improvements could be made to the bedrock models by addition of higher resolution and more consistent geological interpretation to the deeper surfaces.

Future work aims to address comments made from ASK network users and hopefully to include data provided by them.

These models supercede the published BGS 1: 10 000 scale maps of the Glasgow area. Updates in line with advances made in geological understanding of the area during 3D modelling are yet to be made to the maps.

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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.

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