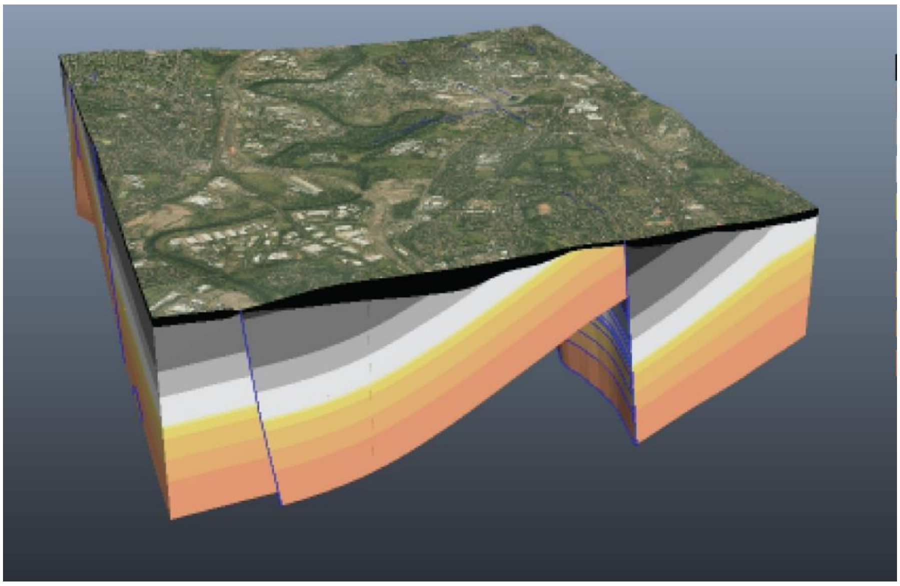
Model metadata report for Glasgow Observatory post-drill bedrock and mine model

UK Geoenergy Observatories Programme

Open Report OR/21/017



BRITISH GEOLOGICAL SURVEY

UK GEOENERGY OBSERVATORIES PROGRAMME

OPEN REPORT OR/21/017

Model metadata report for Glasgow Observatory post-drill bedrock and mine model

T Kearsey, J Burkin

Keywords

3D model, UKGEOS, Glasgow, geothermal, coal mines.

Map

Sheet NS66SW, 1:10 000 scale, Rutherglen

Front cover: Image of the bedrock model, looking west Aerial photography © UKP/Getmapping Licence No. UKP2006/01

Bibliographical reference

KEARSEY, T AND BURKIN, J. 2021. Model metadata report for Glasgow Observatory post-drill bedrock and mine model. *British Geological Survey Open Report*, OR/21/017. 23pp.

Keyworth, Nottingham British Geological Survey 2021

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Contents

FIGURES

TABLES

Summary

This report describes the creation of a 3D geological model developed by the British Geological Survey (BGS) for the UK Geoenergy Observatories (UKGEOS) Glasgow Observatory. The model represents the bedrock geology, fault network, and underground mine workings. The model covers an area of 5 by 4 km with a grid resolution of 50 m and smooths out some of the metre scale variability cause by facies variation and faulting.

The 3D geological model described here uses subsurface data that was collected during the construction of the Observatory, as well as legacy data, and represents our 'post-drill' understanding of the bedrock and mine geometry. A post-drill superficial deposits model is also available.

1 Introduction

The Glasgow Observatory post-drill bedrock model described here updates the Glasgow Geothermal Energy Research Field Site pre-drill bedrock model (Burkin and Kearsey, 2019) which itself builds on earlier Central Glasgow v2 bedrock model (Monaghan et al., 2014) and Central Glasgow bedrock models (Monaghan and Pouliquen, 2009; Arkley et al., 2013). This revision was undertaken as part of the UK Geoenergy Observatories (UKGEOS) Project and includes new subsurface data that was collected during the construction of the Observatory, representing our 'post-drill' understanding of the bedrock and mine geometry.

Intended Usage: This model was created to provide a 3D representation of the bedrock geology at and surrounding the Glasgow Observatory. It builds on the pre-drill model by including new information from the boreholes that were drilled. The model is not at 'site' scale but is intended to give an overview of the bedrock structure and mine working extents within a few kilometres of the Observatory.

The post – drill model incorporates:

- All the data from the pre-drill model (Burkin and Kearsey, 2019)
- The geological information from boreholes GGA01, GGA02, GGA03r, GGA04, GGA05, GGA07, GGA08, GGB05, GGC01.

The base of the model was set to the base of the Scottish Lower Coal Measures Formation and the top is 50 m above Ordnance Datum (OD). The XY extent of the model in British National Grid coordinates is from 260000 660850 to 265000 665000 (i.e. 5 by 4 km), and fits mostly within the Rutherglen 1:10 000 Geology Series Map Sheet (NS66SW; British Geological Survey, 2008). The Glasgow Observatory bedrock model is suitable for use at scales between 1:10 000 and 1:50 000. The grid resolution used in the modelling for the surfaces is 50 m. The model has an average vertical error of 0.1 m (maximum observed vertical error 17 m).

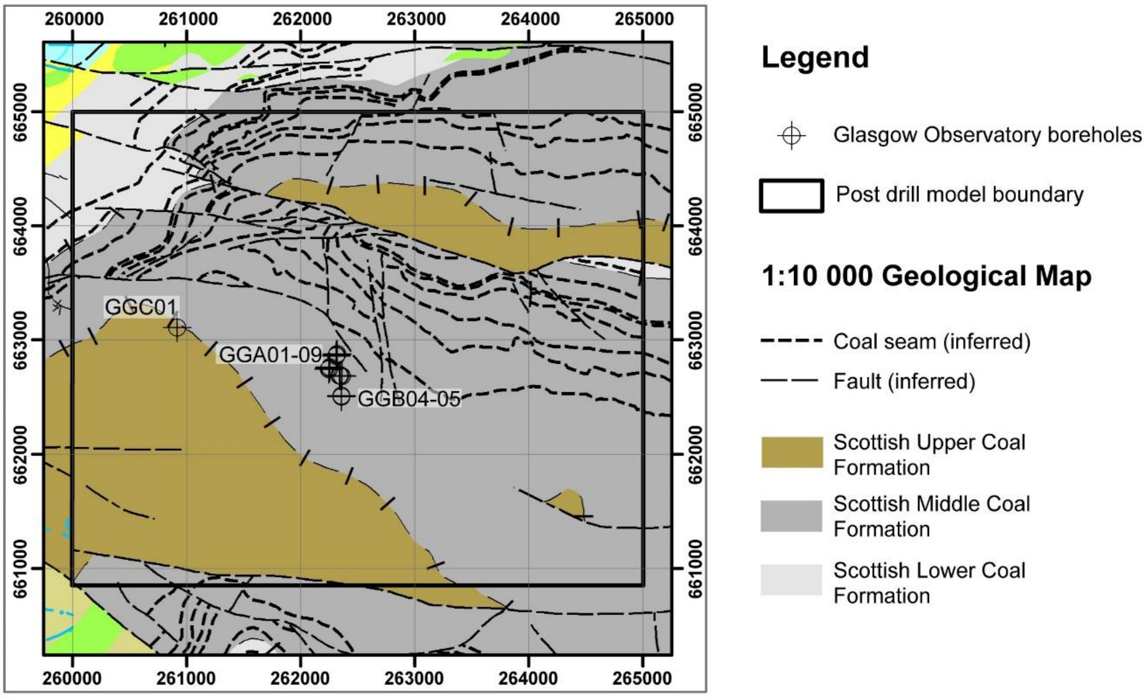

Figure 1 Map showing model area and Observatory boreholes. Geological map data BGS Geology 10K BGS©UKRI

1.1 CITATION GUIDANCE

Any use of the models should be cited to:
Bedrock model DOI: Kearsey, T and Burkin, J. (2021) *(*UKGEOS) Glasgow post-drill bedrock model. NERC EDS National Geoscience Data Centre. (Dataset). https://doi.org/10.5285/369bc803-ddc1-47bc-b9f8-9cffa5ab659e ***Coal mine model*** DOI: Kearsey, T and Burkin, J. (2021) *(*UKGEOS) Glasgow post-drill coal mine model. NERC EDS National Geoscience Data Centre. (Dataset). https://doi.org/10.5285/1f19a50c-b600-4f63-9512-e6c94f79d49c
and this report cited as:
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2 Modelled Surfaces/Volumes

The model contains 13 boundaries which define 12 geological units. All units were considered to be conformable apart from the base Quaternary unconformity termed rockhead (base of superficial deposits). The stratigraphic column used in the model can be seen in Figure 2.

This model only covers the bedrock geology of the area. A GSI3D model of the overlying superficial deposits (Arkley and Callaghan, 2021) has been created. These two models used the same datasets but have not been fitted together because they were built with different modelling algorithms; implicit for the bedrock and explicit for the superficial deposits.

Below is a list of the modelled surfaces with the name in the model and the equivalent BGS Lexicon code in brackets or surface name:

- Topo = Central Glasgow digital terrain model (DTM; 50 m resolution)
- Rockhead = Quaternary unconformity, base of superficial deposits
- TopMiddleCoalMeasuresFormation = base of Scottish Upper Coal Measures Formation (UCMS)
- GlasgowUpperCoal = Glasgow Upper coal (GU)
- GlasgowEllCoal = Glasgow Ell coal (GE)
- GlasgowMainCoal = Glasgow Main coal (GMA)
- HumphCoal = Humph coal (HUC)
- GlasgowSplintCoal = Glasgow Splint coal (GSP)
- VirginCoal = Virgin coal (VI)
- AirdrieBlackBandCoal = Airdrie Black Band coal (ABBC)
- AirdrieVirtuewellCoal = Airdrie Virtuewell coal (AV)
- KiltongueCoal = Kiltongue coal (KILC)
- BaseLowerCoalMeasures = base of Lower Coal Measures (LCMS)

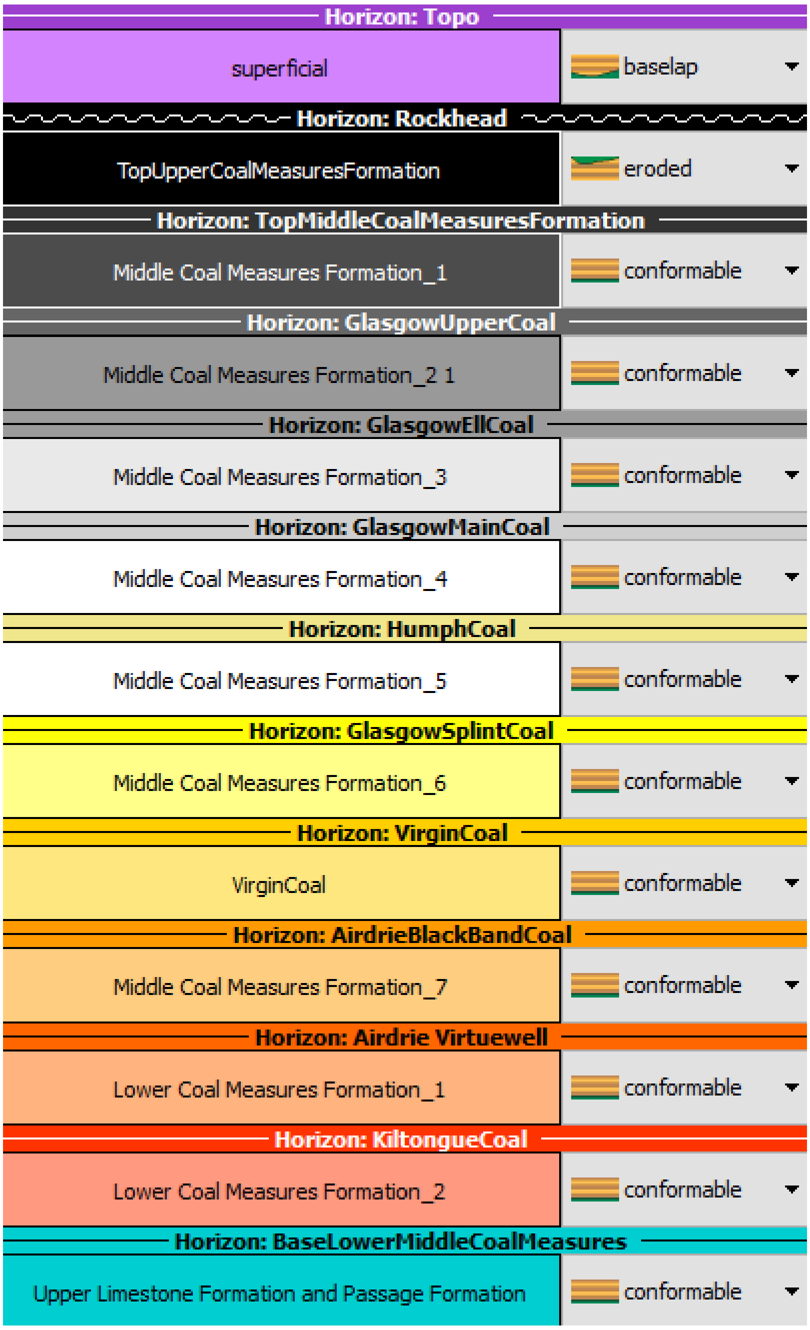

Figure 2 Stratigraphic column showing the modelled surfaces.

3 Modelled Faults

Faults generated from the GOCAD surfaces of the Central Glasgow v2 model (Monaghan et al. 2014) and were input in to the SKUA workflow as top and base lines derived from the original GOCAD surfaces. Fault dips and subsurface locations were derived from mine plan information (where present) and taken from the 1:10 000 scale geological map (BGS, 2008). Figure 3 shows the faults that were included in the model.

Within the model area, faults that have previously been modelled by Monaghan et al. (2014) have retained their designated name (for example, f14, f15, f23). Slight changes were made to previous fault interpretations so that fault geometries better fit with faults identified in mine abandonment plans.

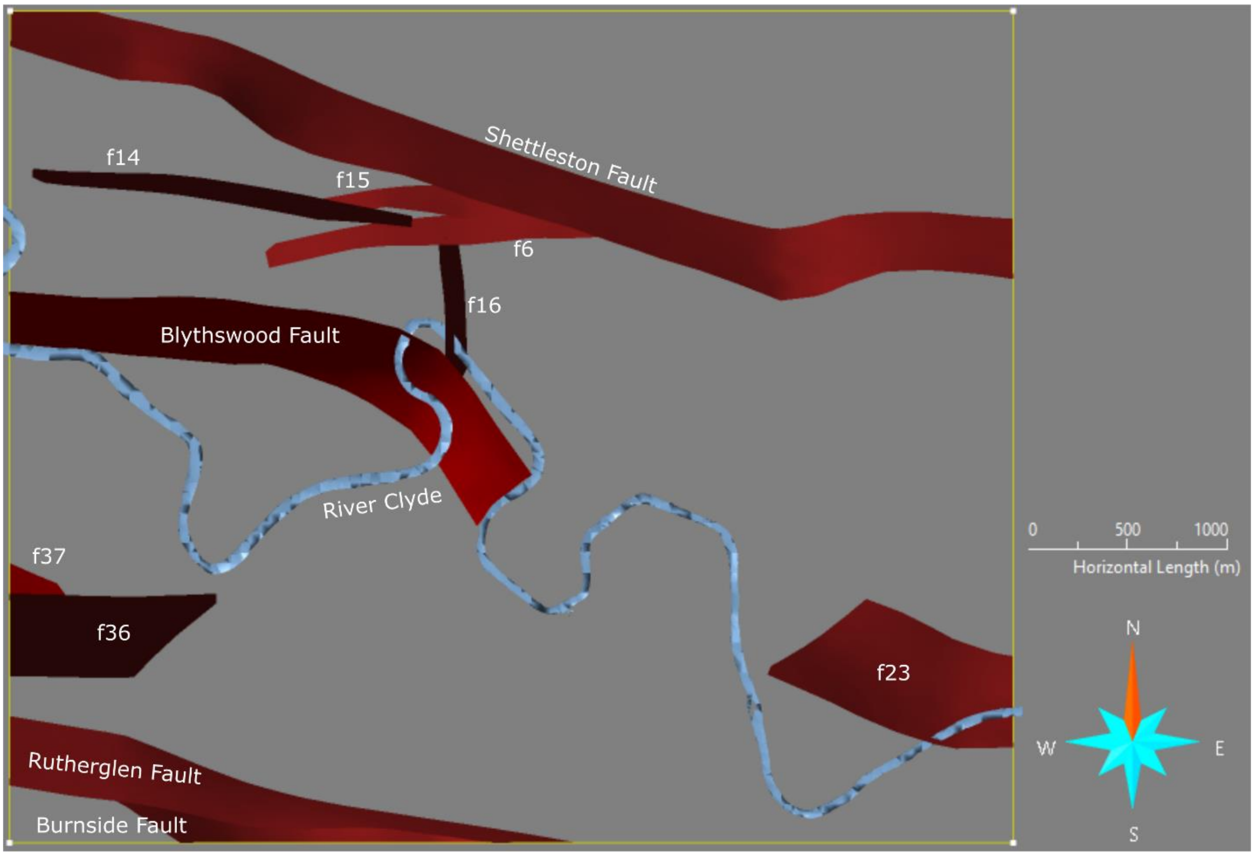

Figure 3 Modelled faults within the model area. Note the truncation of many of the faults by the model extent boundary. River Clyde is shown for geographic reference.

4 Model Workflow

The standard SKUA-GOCAD version 19 ‘Structure and Stratigraphy’ (SnS) workflow was used to create a volumetric model.

The workflow consists of:

- Data compilation and creation of a stratigraphic column (Figure 2)
- Fault modelling including the creation of a fault network and fault blocks (Figure 3)
- Modelling the horizons (Table 1)
- Creation of the geological grids – 3D meshes (Figure 7)

The model was then checked (see Section 8), amended, and exported in various formats (

Table 4). Outside of the SnS workflow, manual techniques have been used to model manmade features such as mine workings, shafts, and underground roadways.

The mine workings were modelled by creating triangulated surfaces (Tsurfs) from the modelled coal seam horizons and ‘stencilling’ out the mine abandonment plan extents that have been captured in GIS shapefile format.

5 Model Datasets

Table 1 lists the datasets that were used in the construction of the modelled horizons. Not all input data available was used in the modelling process. For example, a subset of borehole data was excluded outside of the modelled subcrop extent. Inconsistencies were caused by new borehole data available since the 1:10,000 scale map and where the complexity of the mapped rockhead surface was not reflected in the modelled grid resolution.

Horizon	RH	MCMS	GU	GE	GMA	HUC	GSP	VI	ABBC	AV	KILC	LCMS
Map crop outlines		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mine working levels			✓	✓	✓	✓	✓	✓	✓	✓	✓	
Borehole markers	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Borehole points	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 1 Data used to create modelled horizons. Abbreviations explained in section 2 above.

Borehole markers and points have been extracted from BGS's borehole database that includes stratigraphic interpretations.

5.1 BOREHOLE DATA

Borehole data was recalled using the 'BGS Magpie' application in Access 2016 linked to the BGS corporate Borehole Geology database. This data provides stratigraphic boundaries representing the top or base of known coals or formations, interpreted by various BGS geologists. The Magpie application selects the deepest instance of any particular stratigraphic boundary in individual boreholes. The borehole interpreters selected in this order of preference were, Anthony Irving (AAMI), Alison Monaghan (ALS), Eileen Callaghan (ECAL), Timothy McCormick (TMCM), and David Low (DJLO).

The borehole data was checked and edited to include only markers recording the base of the stratigraphic interval or interest/top of the underlying interval. These XYZ borehole data points were loaded to SKUA as either borehole data points, or 'well markers' for boreholes constraining the greatest number of stratigraphic boundaries.

The post-drill model also includes the information from the 9 of 12 boreholes that were drilled as part of the Glasgow Observatory and penetrated bedrock (3 boreholes only penetrated to superficial deposits). These are described in Barron *et al*. (2020a,b); Monaghan *et al*. (2020a,b); Kearsey *et al.* (2019); Shorter *et al.*(2020); Starcher *et al*. (2020a,b); Walker-Verkuil *et al.,* (2020). Table 2 shows the depths in the boreholes of the of the stratigraphic surfaces that were included in the model. These were integrated with the borehole data included in the pre-drill model and then the model was re-calculated.

	GGC01	GGA01	GGA02	GGA03r	GGA04	GGA05	GGA07	GGA08	GGB05
RH	30.70	26	27.00	27.4	37.7	37.5	35	33.8	40
Top Middle Coal Measures	32.50	eroded	eroded		eroded				
Base Glasgow Upper Coal	95.96	48.86	48.95		50.6	51	53.9	53.7	
Base Glasgow Ell Coal	121.22		70.76			72.6		76.5	
Base Glasgow Main Coal	132.60					85.36		90.7	
Base Humph Coal	146.5								
Base Glasgow Splint Coal	155.35								
Base Virgin Coal	not observed								
Airdrie Blackband Coal	174.60								
Base Airdrie Virtuewell Coal	196.60								

Table 2 The drilled depth in metres from drilling platform of the stratigraphic horizons identified in the Glasgow Observatory boreholes

The SKUA workflow determined that some of the markers on the boreholes were inconsistent and were excluded from the modelling. This is likely because the thickness of the units in these boreholes is at variance with surrounding boreholes, or the boreholes intersect modelled faults but have no fault recorded in the borehole record

5.2 MINING DATA

Mine working levels (XYZ points) from digitised mine abandonment plans were used to constrain the 3D geometry of coal seam horizons.

Mine working levels were included in the SKUA workflow as ‘picks’, meaning that they guide the modelled horizons in the same manner as seismic data. That is, if there is a mismatch between a borehole marker and modelled interval thicknesses, the mine working level will not be honoured exactly.

The GIS files detailing the extent of the mine workings are separated into two classes, recorded mine workings and probable mine workings. Probable, unrecorded mine workings have been interpreted by a BGS staff member who was an ex-mining surveyor and is based on the presence of workings proved in boreholes, shafts, adjacent workings indicated on adjacent abandonment plans, and coal subcrop position at rockhead. The presence and extent of the probable mine workings is therefore uncertain.

Where faults cut through worked coal seams, the mine abandonment plan data are able to guide the location of fault planes at depth, as these are reflected as gaps in the mine plan (Figure 3), and occasionally recorded as a fault with downthrow direction and size of throw.

5.3 MAP DATA

The geological map subcrop lines from the 1:10 000 bedrock map were included for all applicable units. The data was taken from BGS (2008) and projected onto the modelled rockhead surface.

6 Model Limitations

6.1 GENERAL

- The SKUA workflow uses a thickness model to calculate horizons to ensure a minimum separation and prevent crossovers. Thicknesses from boreholes which penetrate the most horizons are prioritised. Inconsistent data is then ignored, meaning that there could be important data points excluded and that the model does not fully capture the true lithological variability.
- The full complexity of the geology may not be represented by the model due to the spatial distribution of the data points at the time of model construction and other limitations including those set out elsewhere in this report.
- 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.
- Borehole start heights are obtained from the original records, Ordnance Survey mapping or a digital terrain model. Where borehole start heights look unreasonable, they are checked and amended if necessary in the index file. In some cases, the borehole start height may be different from the ground surface, if for example, the ground surface has been raised or lowered since the borehole was drilled, or if the borehole was not originally drilled at the ground surface.
- 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. boreholes 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.
- 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 (DiGMapGB) may not appear in or perfectly match the geological model or vice versa. Modelled units are coloured differently to the equivalent units in the published geological maps.
- 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.

6.2 BEDROCK

- The mismatch data (Table 3) provides an overview of how well the modelled horizons intercept the borehole 'well markers'. Within the workflow, well markers can be fitted exactly, resulting in an overly 'dimpled' surface. The approach taken in this model was to allow some smoothing of horizons to best fit the majority of markers (minimising the mismatch) whilst giving a consistent geological model. (see further discussion in section 8)
- The Glasgow Splint Coal and Virgin Coal are modelled very close together, and this is based on their relationship in the data. For example, they are commonly 4 m apart in the model. Clough et al. (1920) surmise that these two seams are occasionally united, and often close enough to form a single working.
- Towards the south-eastern corner of the model, where the top of the Middle Coal Measures interacts with f23, the two slices of horizon differ notably from published

interpretations. The two small patches are a result of a shallow dip interacting with a relatively bumpier rockhead horizon.

6.3 FAULTS

- Faults with less than 30 m of throw have not been modelled meaning that small-scale faulting is unrecognised in the data and may account for mismatch and model inaccuracies.

6.4 MINE WORKINGS

- The extent of mine abandonment plans suggests additional unmodelled minor faults at the intersection of Dechmont and Rutherglen faults (Figure 4) that have not been included in the model.
- Some locations of probable mine workings correlate to locations where the corresponding seam is not modelled. This due to the model being a simplified representation of reality. Some areas of geological complexity (i.e. highly folded, faulted, or speculative interpretations), have been simplified in the modelling process

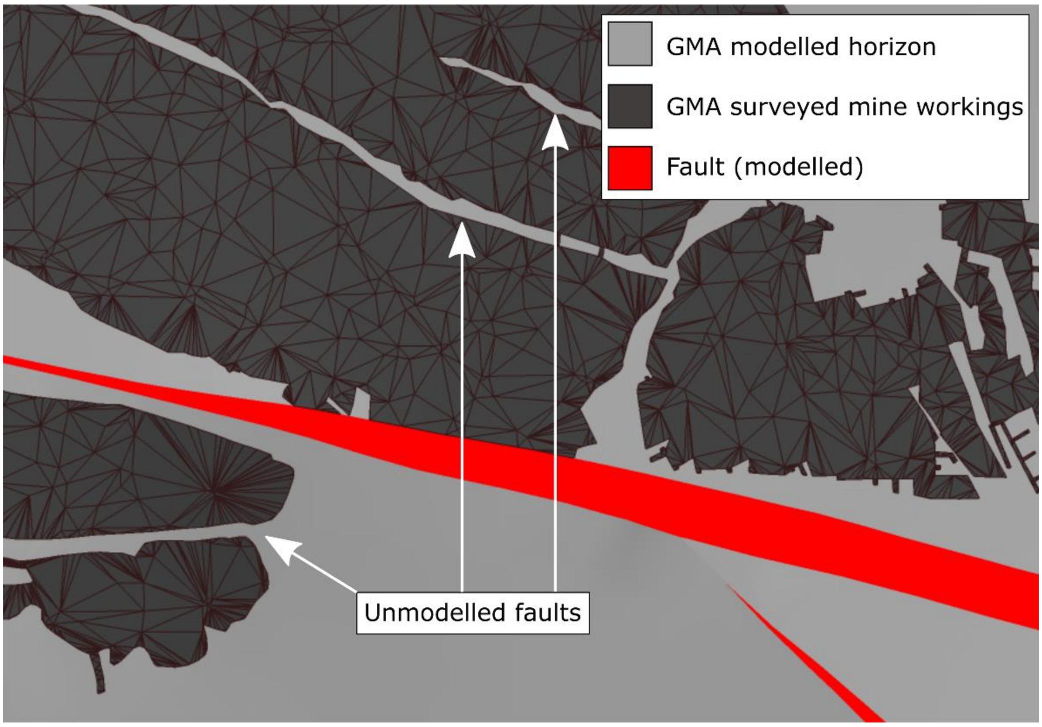

Figure 4 Glasgow Main Coal mine workings showing that there are unmodelled minor faults near the Rutherglen fault.

6.5 FIT WITH SUPERFICAL MODEL

- This model only covers the bedrock geology of the area. A GSI3D model of the overlying superficial deposits (Arkley and Callaghan 2021) has been created. These two models have not been fitted together because they were built with different modelling algorithms; implicit for the bedrock and explicit for the superficial.

7 Model Quality Assurance

In order for a geological model to be approved for publication or delivery to a client a series of quality assurance (QA) checks are carried out. This includes visual examination of the modelled surfaces and fit to datasets. The modelled geological surfaces 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 (http://www.bgs.ac.uk/lexicon/home.html) and the BGS Rock Classification Scheme (http://www.bgs.ac.uk/bgsrcs/) are used as far as possible.

Any issues found in the QA checking process are recorded and addressed before delivery/publication of the model.

8 Model Uncertainty

Input data and interpretations for geological modelling sometimes provide conflicting evidence regarding the location of horizons and geological features. During the modelling workflow, these conflicts are often flagged and options are available to resolve inconsistencies. Not all of these inconsistencies can be remedied, so SKUA minimises errors to the input data

For example, the pre-drill model (Burkin and Kearsey, 2019) noted that SKUA takes borehole 'well markers' as the strongest guidance for the geometry of the subsurface. However due to the variable data density and local complexities in geology that are smaller than the 50 m modelled grid size, not all of the modelled horizons will perfectly match the input borehole markers (Burkin and Kearsey, 2019).

During the post-drill modelling, a method was trialled so see whether the model accuracy could be improved. The model was fitted to the data using the 'honour well markers' function. This reduced the errors, however, it introduced significant spikes and pits in to the modelled surfaces (Figure 5). Between the fitted and unfitted models, the average error only decreased by 0.04 metres. So, although the process of honouring well markers had a negative effect on the visual appearance of the surfaces, it did not significantly change the overall fit to well markers. This may suggest that by trying to improve the accuracy of the model to the boreholes the model has become 'overfitted'. The final post-drill model is therefore the 'unfitted' version.

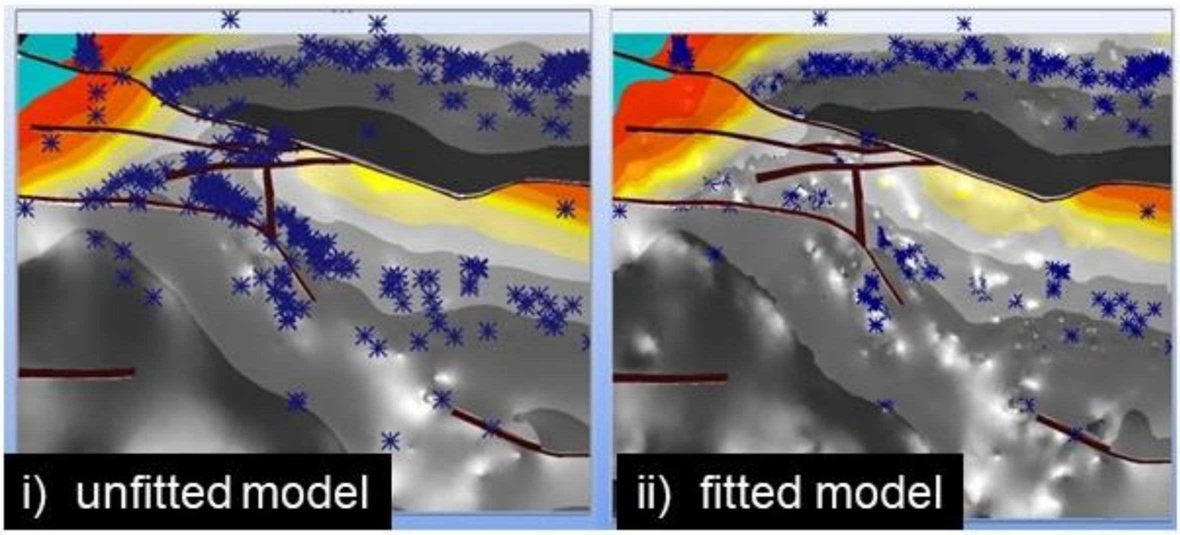

Figure 5 Example of the i) unfitted and ii) fitted model which has been fitted exactly to well marker to data. Note the fitted model has a pitted surface.

The accuracy of the model can be examined as the difference between the final model and the input borehole data points (Table 3). This shows that for all the coal seams, the average error was less than one metre. However, the Glasgow Ell and Glasgow Main coals have borehole data points where the modelled surface is 17.76 m and 11.46 m, respectively, too shallow.

	Final model		
	Min.	Ave.	Max.
Top Middle Coal Measures Formation	-2.73	-1.84	-0.97
Glasgow Upper Coal	-9.69	0.08	3.78
Glasgow Ell Coal	-17.76	-0.04	6.69
Glasgow Main Coal	-11.46	0.07	5.94
Humph Coal	-2.89	0.00	2.90
Glasgow Splint Coal	-6.24	0.03	3.48
Virgin Coal	-4.03	0.06	4.57
Airdrie Black Band Coal	-1.40	0.02	1.45
Airdrie Virtuewell Coal	-2.51	0.26	3.03
KiltongueCoal	-4.42	0.16	6.70
Base Lower Middle Coal Measures	-2.25	0.02	2.03

Table 3 The difference in metres between the modelled surface and borehole data points (minimum, average, maximum)

When the largest errors are investigated the borehole with a 11.46 m difference from the modelled surface of the Glasgow Main Coal and the borehole data point is in a fault splay structure which connects the Shettleston fault to the Blythswood fault (Figure 6). It is not surprising that this area is more complicated than modelled. The borehole with a 17.76 m difference from the modelled surface of the Glasgow Ell Coal is in an area of high borehole density and has boreholes with 40 m distance which show the same horizon at 10 m shallower. This suggests that this borehole may have misidentified the position of the Glasgow Ell Coal.

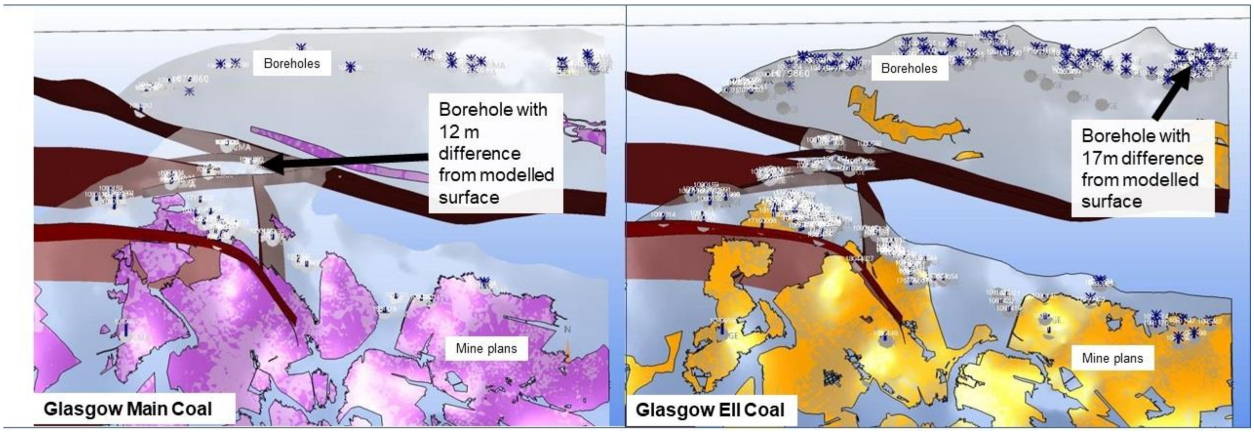

Figure 6 The locations (arrows) of the two boreholes with differences greater than 10 m from the modelled surfaces

9 Model Exports

The modelled horizons, faults, mined seams (recorded and probable), and roadways (coal and stone roads) have been exported to SKUA surfaces (.ts) as well as the GIS compatible ASCII grid format (.asc) (Table 4).

Export type	File format	Approximate size
SKUA tsurf	.ts	~4 MB
ESRI ASCII grid (1 m x 1 m)	.asc	~200 MB
ESRI ASCII grid (5 m x 5 m)	.asc	~10 MB

Table 4 Summary of model export types with typical file sizes.

The SKUA surfaces are created with irregular triangles of varying size from approximately 50 m wide in areas of low variability, down to triangles approximately 1 m wide on curved edges or in mine workings. The ASCII exports on the other hand have uniform cell sizes of 1 m and 5 m, in order to capture the outline of horizons and the sometimes intricate mine outlines of worked coal seams. It is therefore important to understand that the resolution of the exported surfaces is much higher than the resolution that the model was created for. Note there are no are probable mined areas for the GMA within the site area.

10 Model Images and Uses

This section illustrates the post-drill model and various model exports.

The extent and connectivity of the mined underground coal seams, shafts and roadways are likely key hydrogeological features for the low temperature mine water heat energy research to be carried out at the Glasgow Observatory (Figure 11). The 3D geometry of the bedrock also forms a geological framework for hydrogeological modelling (Figure 7 to Figure 10).

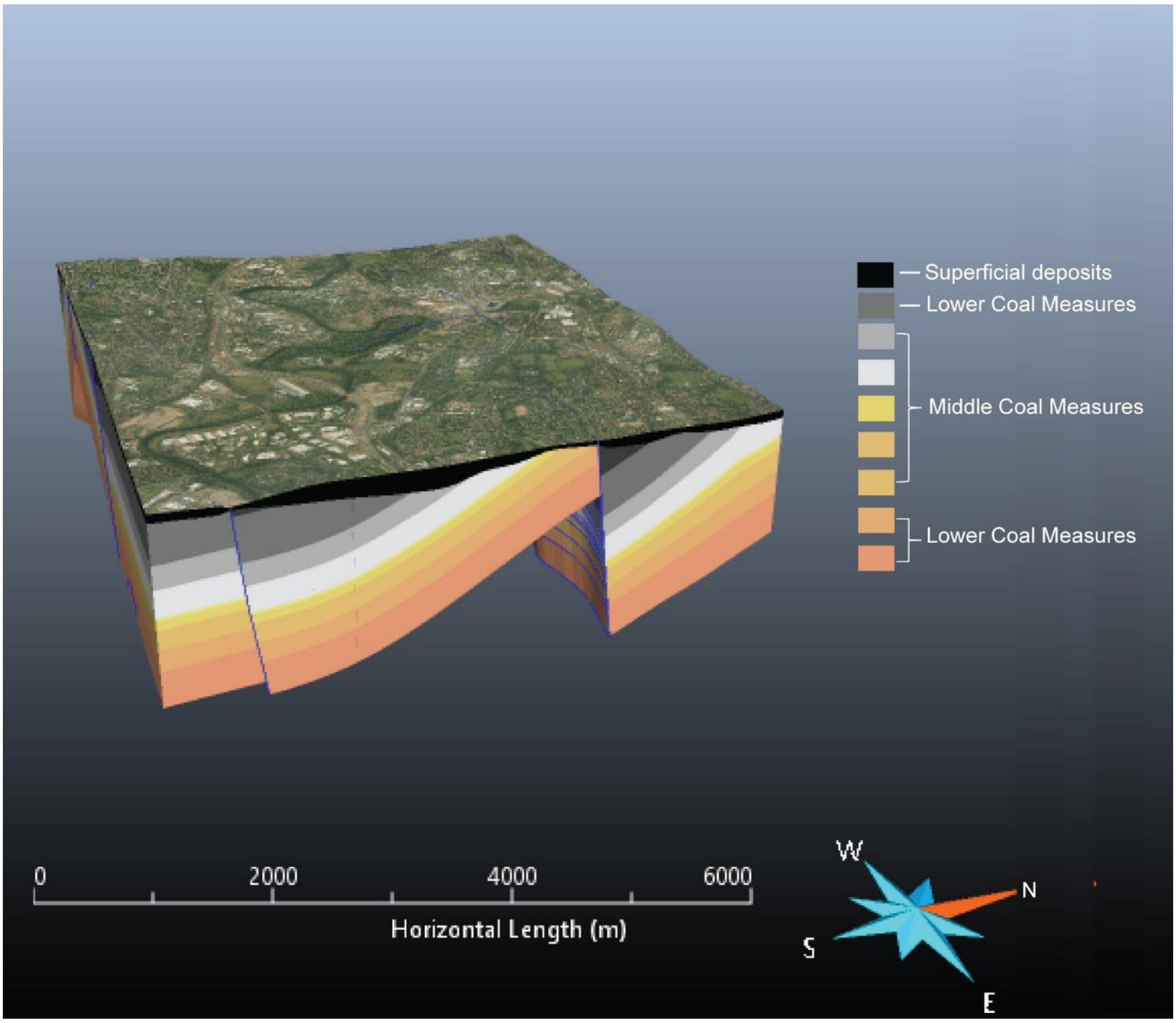

Figure 7 SKUA geological bedrock model, looking from the SE, vertical exaggeration X5. Aerial photography © UKP/Getmapping Licence No. UKP2006/01

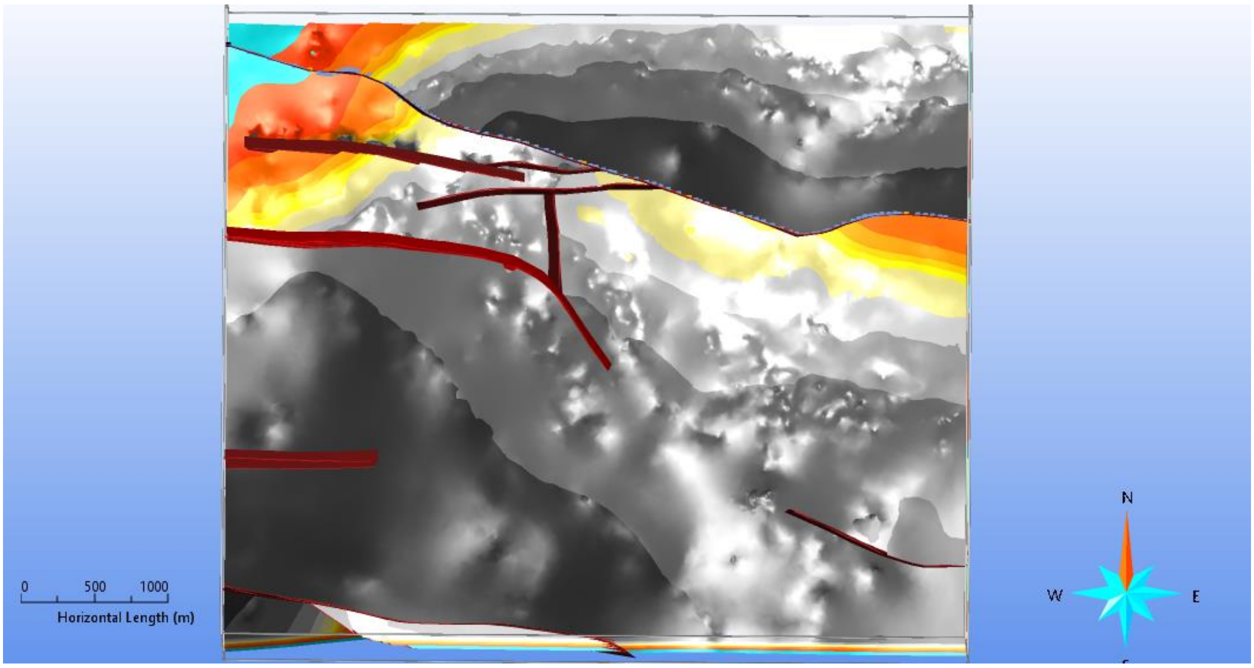

Figure 8 SKUA geological bedrock model, top view, model colours as in Figure 2.

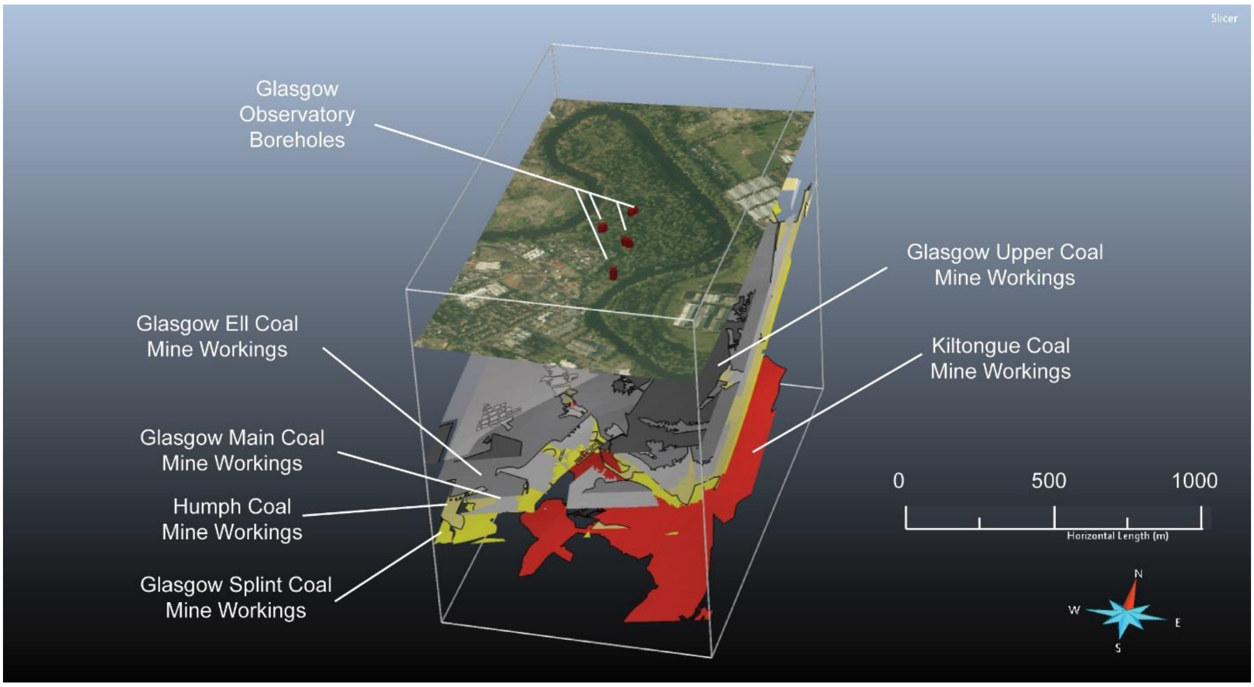

Figure 9 Section of the mine workings from the model under the Glasgow Observatory site illustrating the stack of recorded mine workings and shafts of the worked seams in the Scottish Coal Measures Group. Vertical exaggeration x5. Cut out of the geological model.

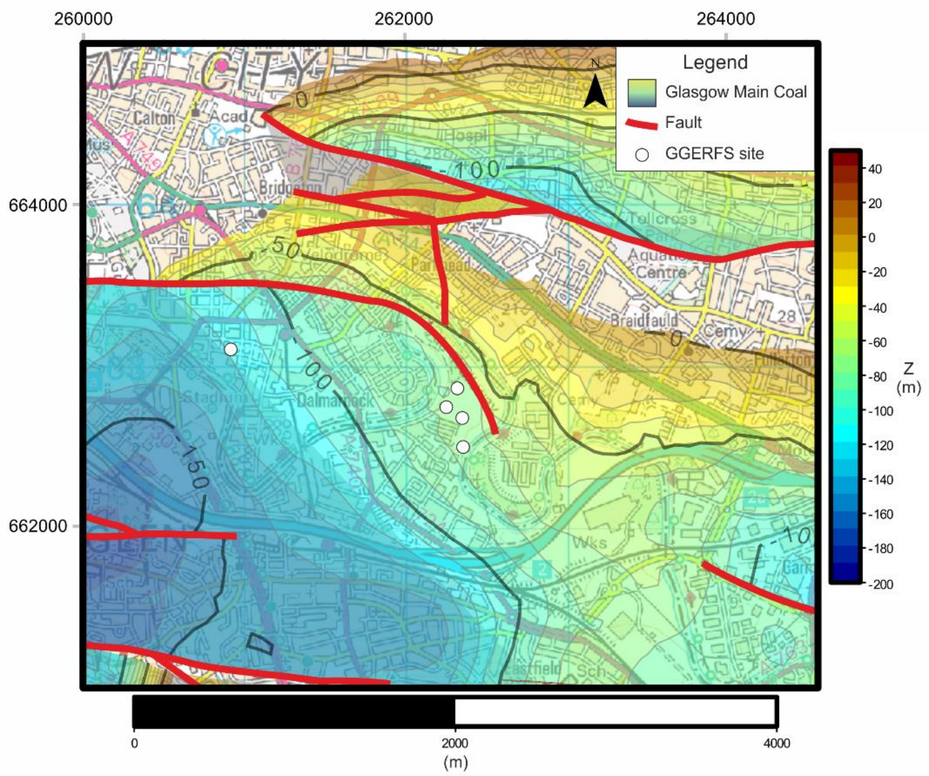

Figure 10 Contoured depth grid (metres relative to Ordnance Datum) for the base of Glasgow Main Coal, horizon exported from the geological model showing the closed synclinal structure and variety of fault trends. All rights reserved. Contains Ordnance Survey data © Crown copyright and database rights. All rights reserved 2021 Ordnance Survey 100021290 EUL.

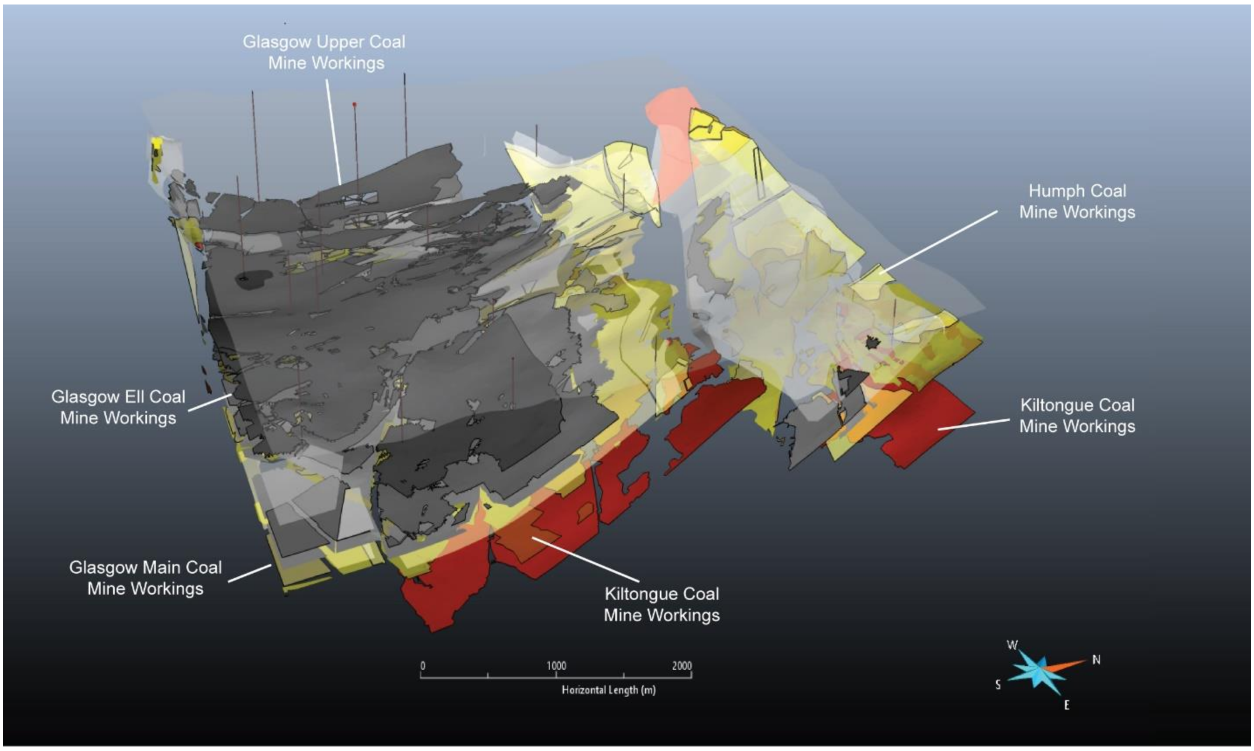

Figure 11 Isometric view from the southwest showing the extent and stack of recorded mine workings of the worked seams in the Scottish Coal Measures Group cut out of the geological model, to illustrate the extent and connectivity of the potential mine water geothermal resource.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details).

ARKLEY, S. 2019. Model metadata report for the Glasgow Geothermal Energy Research Field Site superficial deposits model. British Geological Survey Open Report, OR/18/064, 50pp, http://nora.nerc.ac.uk/id/eprint/524556/

ARKLEY S AND CALLAGHAN E. 2021. Model metadata report for the Glasgow Observatory post-drill superficial deposits model. British Geological Survey Open Report, OR/21/034, 52pp

ARKLEY S, WHITBREAD K, MONAGHAN A. 2013. Clyde superficial deposits and bedrock models released to the ASK Network 2013: a guide for users. *British Geological Survey Open Report,* OR/13/002. 25pp. (Unpublished)

BARRON, H F, STARCHER, V, MONAGHAN, A A, SHORTER, K M AND WALKER-VERKUIL, K. 2020a. Mine water characterisation and monitoring borehole GGA05, UK Geoenergy Observatory, Glasgow. *British Geological Survey Open Report*, OR/20/025, 35pp. http://nora.nerc.ac.uk/id/eprint/528052/

BARRON, H F, STARCHER, V, WALKER-VERKUIL, K, SHORTER, K M AND MONAGHAN, A A. 2020b. Mine water characterisation and monitoring borehole GGA08, UK Geoenergy Observatory, Glasgow. *British Geological Survey Open Report*, OR/20/028, 35pp, http://nora.nerc.ac.uk/id/eprint/528081/

BURKIN, J, AND KEARSEY, T. 2019. Model metadata report for Glasgow Geothermal Energy Research Field Site bedrock model. *British Geological Survey Open Report*, OR/18/053. 23pp

BRITISH GEOLOGICAL SURVEY. 2008. Sheet NS66SW: Bedrock and Artificial Deposits (Rutherglen) 1:10 000. (Keyworth, Nottingham: *British Geological Survey*

CLOUGH, C T, WILSON, J S G, ANDERSON, E M, MACGREGOR M, CARRUTHERS, R G, DINHAM, C H, 1920. The Economic Geology of the Central Coalfield of Scotland, Area VII (Rutherglen, Hamilton, and Wishaw). Mem. *Geol. Survey, Scotland*. 140pp.

KEARSEY, T, GILLESPIE, M, ENTWISLE, D, DAMASCHKE, M, WYLDE, S, FELLGETT, M, KINGDON, A, BURKIN, J, STARCHER, V, SHORTER, K, BARRON, H, ELSOME, J, BARNETT, M AND MONAGHAN, A. 2019. UK Geoenergy Observatories Glasgow: GGC01 cored, seismic monitoring borehole – intermediate data release. *British Geological Survey Open Report*, OR/19/049 36pp, http://nora.nerc.ac.uk/id/eprint/525009/

MONAGHAN, A A, ARKLEY, S L B, WHITBREAD, K, MCCORMAC, M. 2014. Clyde superficial deposits and bedrock models released to the ASK Network 2014: a guide for users. Version 3. Nottingham, UK, *British Geological Survey*, 31pp. (OR/14/013) http://nora.nerc.ac.uk/id/eprint/505554/

MONAGHAN, A A & POULIQUEN, G. 2009. East End Glasgow bedrock modelling - BGS project document. *British Geological Survey Internal Report*, IR/08/063. 34pp. (Unpublished)

MONAGHAN, A A, STARCHER, V, Ó DOCHARTAIGH, B, SHORTER, K, BURKIN, J. 2018. UK Geoenergy Observatories: Glasgow Geothermal Energy Research Field Site: Science Infrastructure. *British Geological Survey Open Report*, OR/18/037. 46pp. http://nora.nerc.ac.uk/id/eprint/521444/

MONAGHAN, A A, BARRON, H F, STARCHER, V, SHORTER, K M AND WALKER-VERKUIL, K. 2020a. Mine water characterisation and monitoring borehole GGA01, UK Geoenergy Observatory, Glasgow. *British Geological Survey Open Report*, OR/20/021, 28pp. http://nora.nerc.ac.uk/id/eprint/528075/

MONAGHAN, A A, STARCHER, V, BARRON, H F, SHORTER, K M AND WALKER-VERKUIL, K. 2020b. Borehole GGA02, UK Geoenergy Observatory, Glasgow. *British Geological Survey Open Report*, OR/20/022, 31pp, http://nora.nerc.ac.uk/id/eprint/528076/

SHORTER, K M, STARCHER, V, BARRON, H F, WALKER-VERKUIL, K AND MONAGHAN, A A. 2020a. Environmental baseline characterisation and monitoring borehole GGA03r, UK Geoenergy Observatory, Glasgow. *British Geological Survey Open Report*, OR/20/023, 23pp, http://nora.nerc.ac.uk/id/eprint/528077/

STARCHER, V, BARRON, H F, MONAGHAN, A A, SHORTER, K M AND WALKER-VERKUIL, K. 2020a. Mine water characterisation and monitoring borehole GGA04, UK Geoenergy Observatory, Glasgow. *British Geological Survey Open Report*, OR/20/024, 28pp, http://nora.nerc.ac.uk/id/eprint/528078/

STARCHER, V, WALKER-VERKUIL, K, SHORTER, K M, MONAGHAN, A A AND BARRON, H F. 2020b. Mine water characterisation and monitoring borehole GGA07, UK Geoenergy Observatory, Glasgow. *British Geological Survey Open Report*, OR/20/027, 29pp. http://nora.nerc.ac.uk/id/eprint/528080/

WALKER-VERKUIL, K, STARCHER, V, BARRON, H F, SHORTER, K M, ELSOME, J AND MONAGHAN, A A. 2020b. Environmental baseline characterisation and monitoring borehole GGB05, UK Geoenergy Observatory, Glasgow. *British Geological Survey Open Report*, OR/20/031, 23pp, http://nora.nerc.ac.uk/id/eprint/528084/