Borehole GGA02, UK Geoenergy Observatory, Glasgow

UK Geoenergy Observatories Programme

Open Report OR/20/022

BRITISH GEOLOGICAL SURVEY

UK GEOENERGY OBSERVATORIES PROGRAMME

OPEN REPORT OR/20/022

Borehole GGA02, UK Geoenergy Observatory, Glasgow

A A Monaghan, V Starcher, H F Barron, K M Shorter, K Walker-Verkuil

Contributors

J Elsome, J Burkin, O Kuras, P Meldrum, B O Dochartaigh, E Callaghan.

Editor

M Spence

Keywords

Borehole drilling, UKGEOS, mine water heat, mine working, geothermal, bedrock, superficial deposits

National Grid Reference

SW corner 262314,662869
NE corner 262314,662869

Front cover

Borehole drilling of GGA02 at Cuningar Loop, Summer 2019.

Bibliographical reference

MONAGHAN A A, STARCHER V, BARRON H F, SHORTER K M, WALKER-VERKUIL K 2020. Borehole GGA02, UK Geoenergy Observatory, Glasgow. *British Geological Survey Open Report*, OR/20/022. 31pp.

Keyworth, Nottingham British Geological Survey 2020

BRITISH GEOLOGICAL SURVEY

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

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

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

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

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

British Geological Survey offices

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3100

BGS Central Enquiries Desk

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

BGS Sales

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

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

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

Natural History Museum, Cromwell Road, London SW7 5BD

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

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

Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800

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

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

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

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

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

Tel 01793 444000
www.ukri.org

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

Acknowledgements

This report is the culmination of a huge amount of work delivered by many staff from BGS, the UK Geoenergy Observatories contractors BAM Nuttall/ BAM Ritchies, Ramboll, Drilcorp and others. Special thanks go to the UK Geoenergy Observatories Science Advisory Group (GSAG) for on- call support to maximise science opportunities during the construction phase, and to project partners including landowners, local residents and regulatory bodies (in particular Clyde Gateway, SEPA and The Coal Authority). Within BGS the communications and engagement team of C Chapman, C Buchanan and T Galley have had a significant role in enabling the borehole construction, and many BGS data management and informatics experts have had a large part to play in making datasets openly available. G Baxter, R Dearden, J Midgley, S Burke, C Abesser, S Hannis, T Kearsey and S Henderson are also thanked for their input to planning the borehole and the checking of datasets.

Contents

FIGURES

TABLES

Summary

This report and accompanying data release describe the ‘as-built’ borehole GGA02 at the UK Geoenergy Observatory in Glasgow, as well as summarising an initial geological interpretation.

Mine water borehole GGA02 at the UK Geoenergy Observatory in Glasgow encountered the Glasgow Upper and Glasgow Ell mine workings and was screened across an interval interpreted as a completely collapsed Glasgow Main mine working and overlying sandstone roof. Unfortunately, grout entered the inside of the casing in the final stages of borehole construction, cementing up the screened section and resulting in GGA02 being repurposed as a cased, sensor testing borehole. New sensors can be tested inside the uPVC casing to 67.2 m drilled depth. Hydrogeological testing of GGA02 was not possible. Borehole GGA02 has a number of types of sensor cabling installed. Fibre-optic DTS cable is installed between the bedrock uPVC borehole casing and the rock wall with capability to work in passive (monitoring) mode to 72.65 m drilled depth. Fibre-optic cabling is also installed on the outside of the steel superficial deposits casing with the ability for use in active or passive mode. Electrical resistivity tomography cable with the deepest sensor placed at 85.58 m drilled depth is available for cross-borehole monitoring and imaging with the adjacent borehole GGA01.

1 Introduction

Borehole GGA02 was drilled as a mine water borehole at Cuningar Loop in Rutherglen, Glasgow City Region, between 17th June and 20th September 2019 (start of drilling to casing installation date). The borehole targeted the Glasgow Main mine working, with the slotted screen at -68.2 to -72.7 m relative to Ordnance Datum. However, in the final stages of construction, grout was detected inside the borehole, the screened section is cemented up and GGA02 is now available as a sensor testing borehole to -56.29 m relative to Ordnance Datum.

The borehole was drilled as part of a set of six mine water[*], five environmental baseline and a seismic monitoring borehole as part of the UK Geoenergy Observatory in Glasgow. Further details of the purpose and planned infrastructure at the Observatory are described in Monaghan et al. (2019) and a geological characterisation of the area is provided in Monaghan et al. (2017).

This document and accompanying data files provides the definitive information on the ‘as-built’ borehole infrastructure.

- Table 1 and Figure 1 provide a summary of the borehole. Figure 1 is also included in the information release [*Summary_BGS_Log_Page1_GGA02.pdf* and *Summary_BGS_Log_Page2_GGA02.pdf*].
- Appendix A lists the files making up the information release.

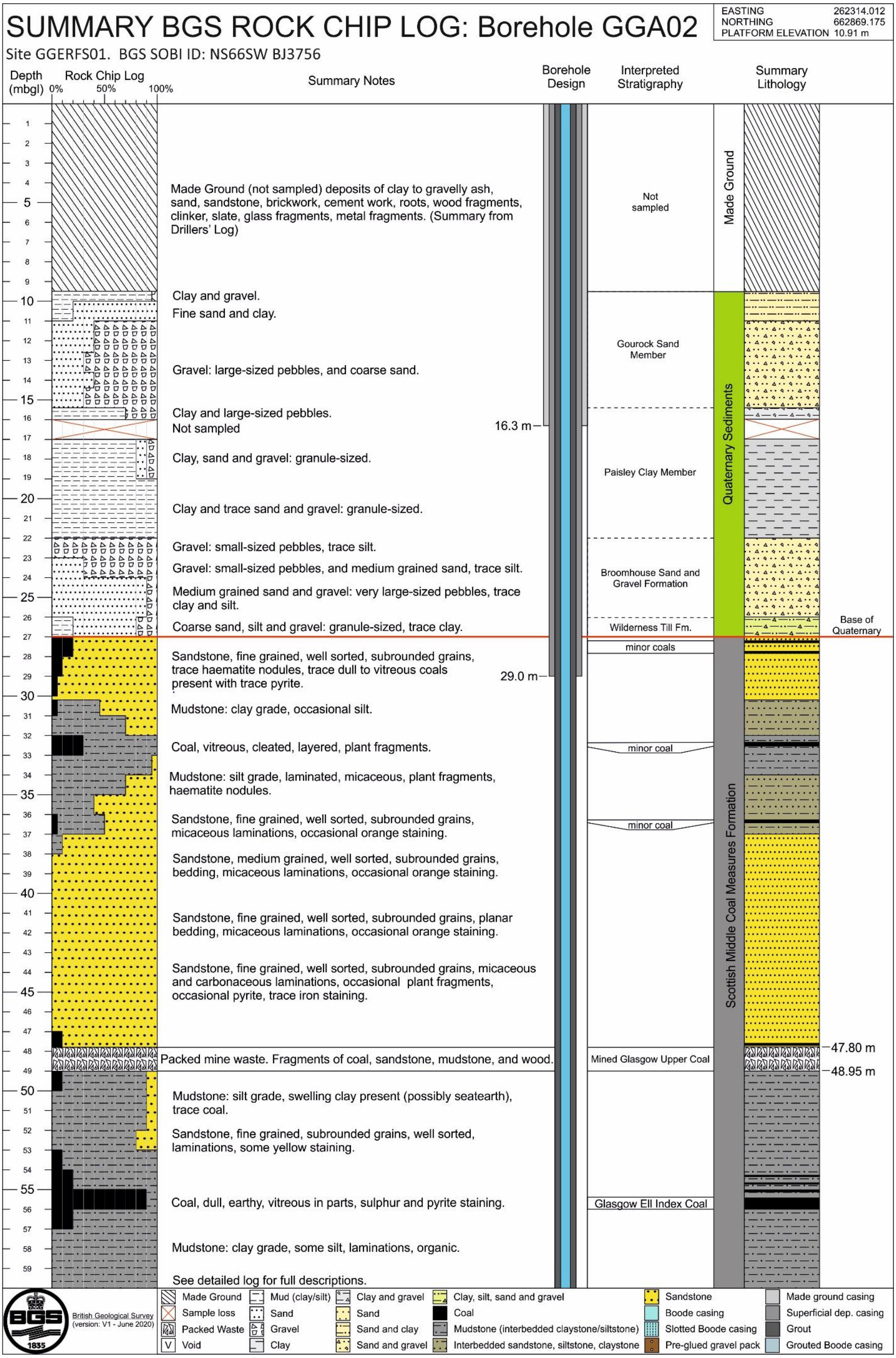
[*] Five boreholes were completed as mine water boreholes and GGA02 was completed as a sensor testing borehole

1.1 CITATION GUIDANCE

Any use of the data should be cited to:
DOI: https://dx.doi.org/10.5285/189dac62-b720-4fde-8260-f129fb9b0233 A A Monaghan, V Starcher, H F Barron, K M Shorter, K Walker-Verkuil. 2020. UK Geoenergy Observatories Glasgow Borehole GGA02 Data Release
and this report cited as:
MONAGHAN A A, STARCHER V, BARRON H F, SHORTER K M, WALKER-VERKUIL K 2020. Borehole GGA02, UK Geoenergy Observatory, Glasgow. British Geological Survey Open Report, OR/20/022.

Table 1 GGA02 as-built summary

Borehole number	GGA02	
Site	GGERFS01	
Easting (British National Grid)	262314.012	
Northing (British National Grid)	662869.175	
Drilling platform level (metres above Ordnance Datum AOD)	10.91	
Drilling started	17/06/2019	
Final casing installed	20/09/2019	
As-built borehole start height or datum (top Boode casing flange, metres AOD)	9.98 (measured as 9.977)	
Installation details		
Borehole detail	**Depths (drill length from drill platform level, metres)**	**Diameter size**
Made ground casing	0.00 – 16.30	24” (610 mm OD x 575 mm ID)
Rockhead casing	0.00 – 29.00	18” (457 mm OD x 425 mm ID)
Boode Well (BW) casing	0.00 – 79.10	280 mm OD x 248 mm ID
BW Slotted pipe	79.10 – 83.60	280 mm OD x 248 mm ID
BW Casing Sump	83.60 – 93.50	280 mm OD x 248 mm ID
Geological details	**Depths (drill length from drill platform level, metres)**	**Depths, relative to Ordnance Datum (m)**
Base of made ground	9.5	+1.41
Base of superficial deposits	27	-16.09
Top Glasgow Upper mineworking	47.8	-36.89
Base Glasgow Upper mine working	48.95	-38.04
Top Glasgow Ell mineworking	70.16	-59.25
Base Glasgow Ell mine working	70.76	-59.85
Top/Base Glasgow Main mineworking	Not recognised	Not recognised
Final drilled length	94.16	-83.25
Final completion depth	67.2	-56.29
BGS SOBI reference number	NS66SW BJ 3756	BGS ID 20693597


SUMMARY BGS ROCK CHIP LOG: Borehole GGA02
EASTING 262314.012
NORTHING 662869.175
PLATFORM ELEVATION 10.91 m
Site GGERFS01. BGS SOBI ID: NS66SW BJ3756
Depth (mbgl)
Rock Chip Log 0% 50% 100%
Summary Notes
Borehole Design
Interpreted Stratigraphy
Summary Lithology
Made Ground (not sampled) deposits of clay to gravelly ash, sand, sandstone, brickwork, cement work, roots, wood fragments, clinker, slate, glass fragments, metal fragments. (Summary from Drillers' Log)
Clay and gravel.
Fine sand and clay.
Gravel: large-sized pebbles, and coarse sand.
Clay and large-sized pebbles.
Not sampled
Clay, sand and gravel: granule-sized.
Clay and trace sand and gravel: granule-sized.
Gravel: small-sized pebbles, trace silt.
Gravel: small-sized pebbles, and medium grained sand, trace silt.
Medium grained sand and gravel: very large-sized pebbles, trace clay and silt.
Coarse sand, silt and gravel: granule-sized, trace clay.
Sandstone, fine grained, well sorted, subrounded grains, trace haematite nodules, trace dull to vitreous coals present with trace pyrite.
Mudstone: clay grade, occasional silt.
Coal, vitreous, cleated, layered, plant fragments.
Mudstone: silt grade, laminated, micaceous, plant fragments, haematite nodules.
Sandstone, fine grained, well sorted, subrounded grains, micaceous laminations, occasional orange staining.
Sandstone, medium grained, well sorted, subrounded grains, bedding, micaceous laminations, occasional orange staining.
Sandstone, fine grained, well sorted, subrounded grains, planar bedding, micaceous laminations, occasional orange staining.
Sandstone, fine grained, well sorted, subrounded grains, micaceous and carbonaceous laminations, occasional plant fragments, occasional pyrite, trace iron staining.
Packed mine waste. Fragments of coal, sandstone, mudstone, and wood.
Mudstone: silt grade, swelling clay present (possibly seatearth), trace coal.
Sandstone, fine grained, subrounded grains, well sorted, laminations, some yellow staining.
Coal, dull, earthy, vitreous in parts, sulphur and pyrite staining.
Mudstone: clay grade, some silt, laminations, organic.
See detailed log for full descriptions.
16.3 m
29.0 m
Not sampled
Gourock Sand Member
Paisley Clay Member
Broomhouse Sand and Gravel Formation
Wilderness Till Fm.
minor coals
minor coal
minor coal
Mined Glasgow Upper Coal
Glasgow Ell Index Coal
Made Ground
Quaternary Sediments
Scottish Middle Coal Measures Formation
Base of Quaternary
47.80 m
48.95 m
British Geological Survey (version: V1 - June 2020)
BGS 1835
Made Ground
Sample loss
Packed Waste
Void
Mud (clay/silt)
Sand
Gravel
Clay
Clay and gravel
Sand
Sand and clay
Sand and gravel
Clay, silt, sand and gravel
Coal
Mudstone (interbedded claystone/siltstone)
Interbedded sandstone, siltstone, claystone
Sandstone
Boode casing
Slotted Boode casing
Pre-glued gravel pack
Made ground casing
Superficial dep. casing
Grout
Grouted Boode casing

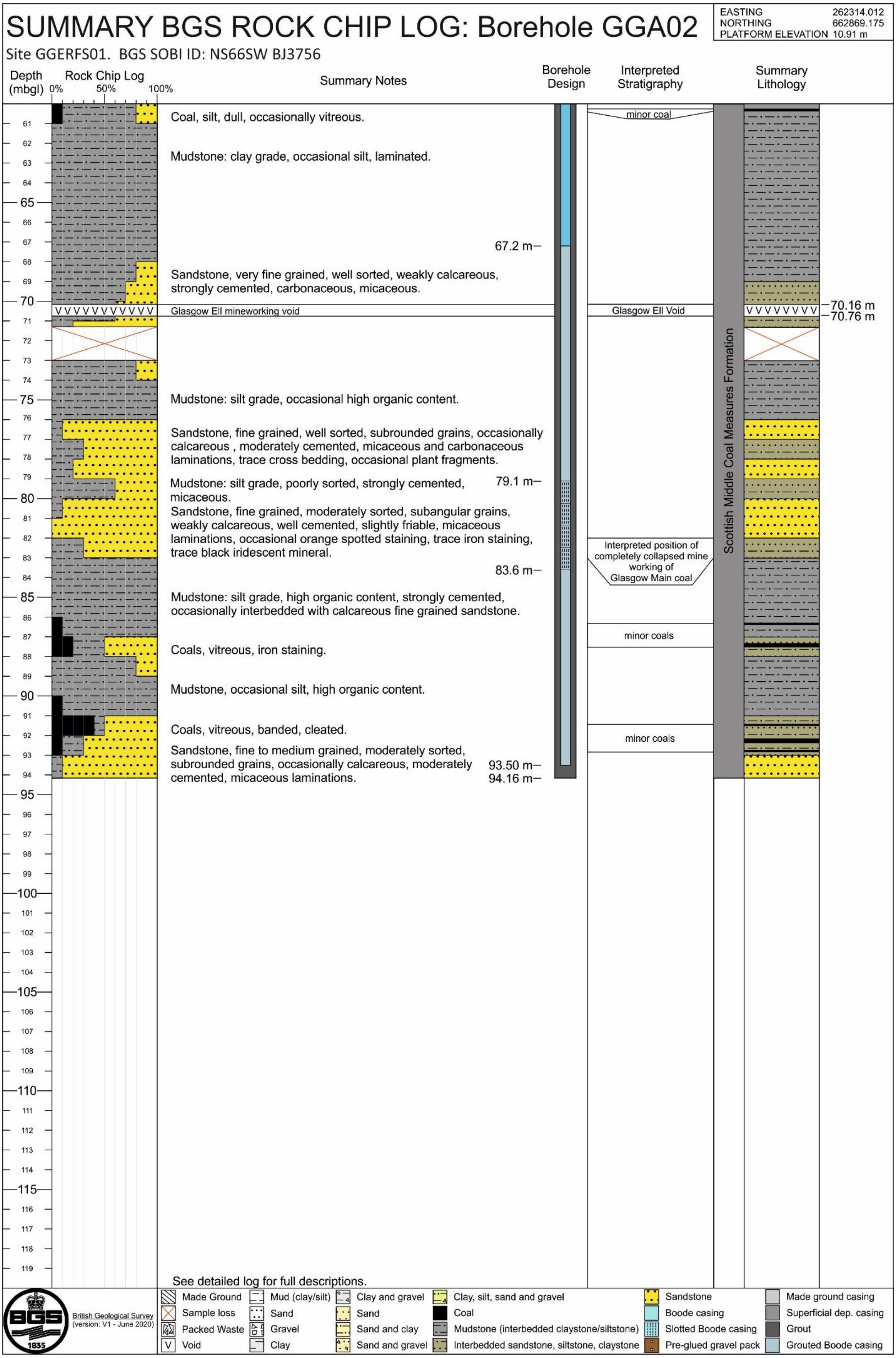


Figure 1 GGA02 summary log based on rock chip returns

1.2 AS-BUILT BOREHOLE LOCATION

Borehole GGA02 is part of the UK Geoenergy Observatory: Glasgow Geothermal Energy Research Field Site (GGERFS) located on the southern side of the River Clyde, South Lanarkshire, four kilometres south-east of Glasgow city centre (Figure 2).

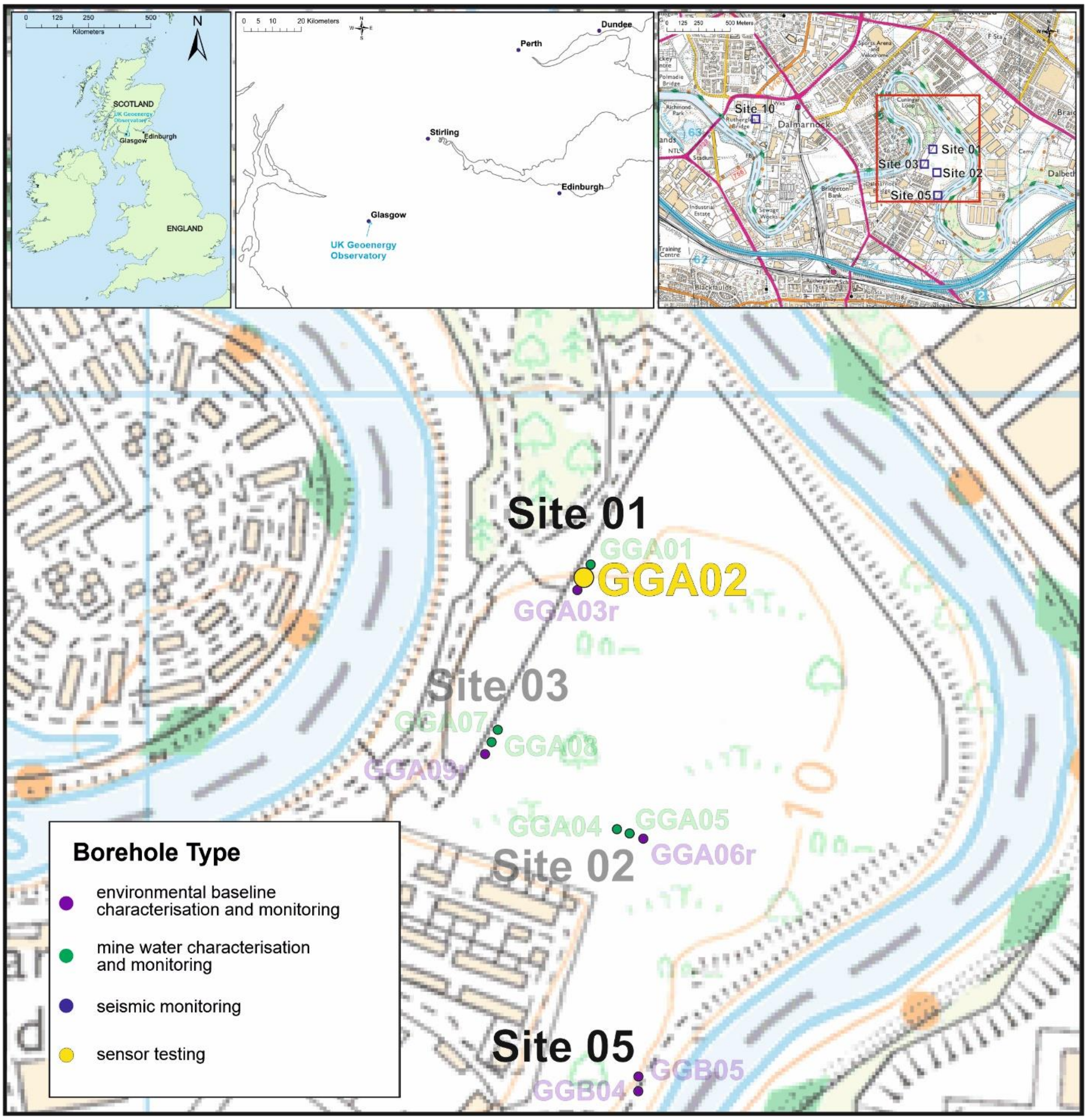


Figure 2 Location map of borehole GGA02, UK Geoenergy Observatory in Glasgow. The other mine water and environmental baseline boreholes are shown for reference. Contains Ordnance Survey data © Crown copyright and database rights. All rights reserved [2020] Ordnance Survey [100021290 EUL].

1.3 DRILLING AND AS-BUILT LENGTHS AND HEIGHTS

Borehole drilling took place from a built-up gravel platform, with the reference datum for drilled depth (measured in metres below ground level; mbgl) being the drilling platform ground level (measured in metres above Ordnance Datum; m AOD; Figure 3). All drillers' logs, sample depths, BGS rock chip logs and wireline logs, together with the stated installation depths of ERT sensors and fibre-optic cables are referenced to the drilling platform level. After drilling had been completed, the borehole casings were cut down and a manhole chamber was installed (Tables 2,3).

The borehole head works were installed in the manhole chamber. The as-built borehole therefore has a different start height or reference datum level, which is the top of the blue Boode casing flange (Figure 3). Depths down the borehole can be expressed as lengths from the top Boode casing, or relative to Ordnance Datum (Tables 2,3).

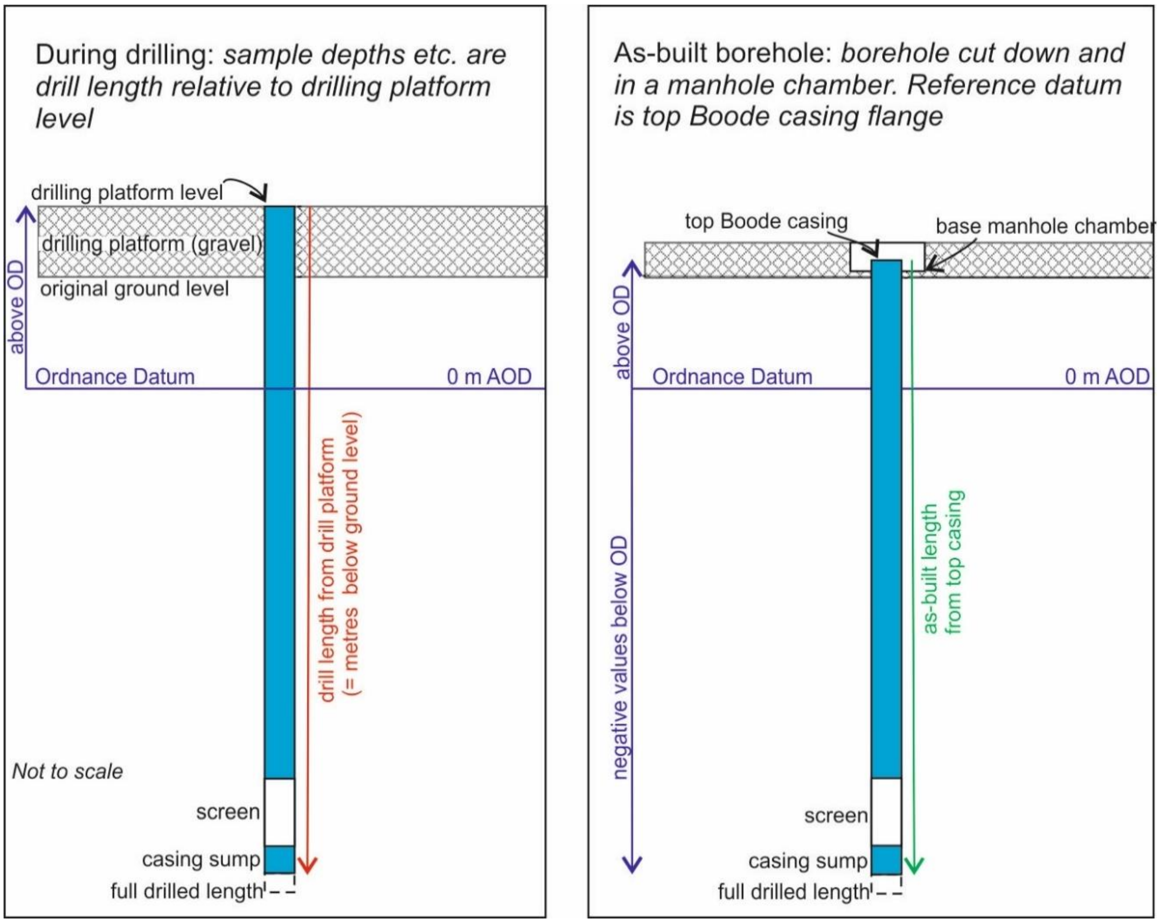


Figure 3 Images summarising the datums and depths/lengths/heights during drilling (left) and as-built (right)

Table 2 Summary of start heights and datums used for GGA02

Stage	**Borehole start height/ reference datum used (m AOD)**	**Used in**
Drilling platform level – built up gravel platform	10.91	Drillers and BGS logs, sample depths, wireline log. ERT and DTS cable installation.
As-built borehole start height (top Boode casing flange)	9.98 (recorded as 9.977)	Reference datum for future Observatory users
Conversion Rock chip sample depths, wireline depths – to convert from drill length to beneath as-built borehole start height		As-built depth below start height = drill length – (10.91 – 9.98) m *i.e* As-built depth below start height = drill length – (0.93) m

2 As-built borehole design

The Glasgow Geoenergy Observatory boreholes have been designed for a range of scientific research purposes over a 15-year lifetime, with 2 sets of sensor cables installed on the outside of the bedrock casing (mine water boreholes). GGA02 also has fibre-optic cabling on the outside of the superficial deposits casing (Figure 4). As such, their construction is not typical of mine water or environmental monitoring boreholes that would be installed for commercial schemes.

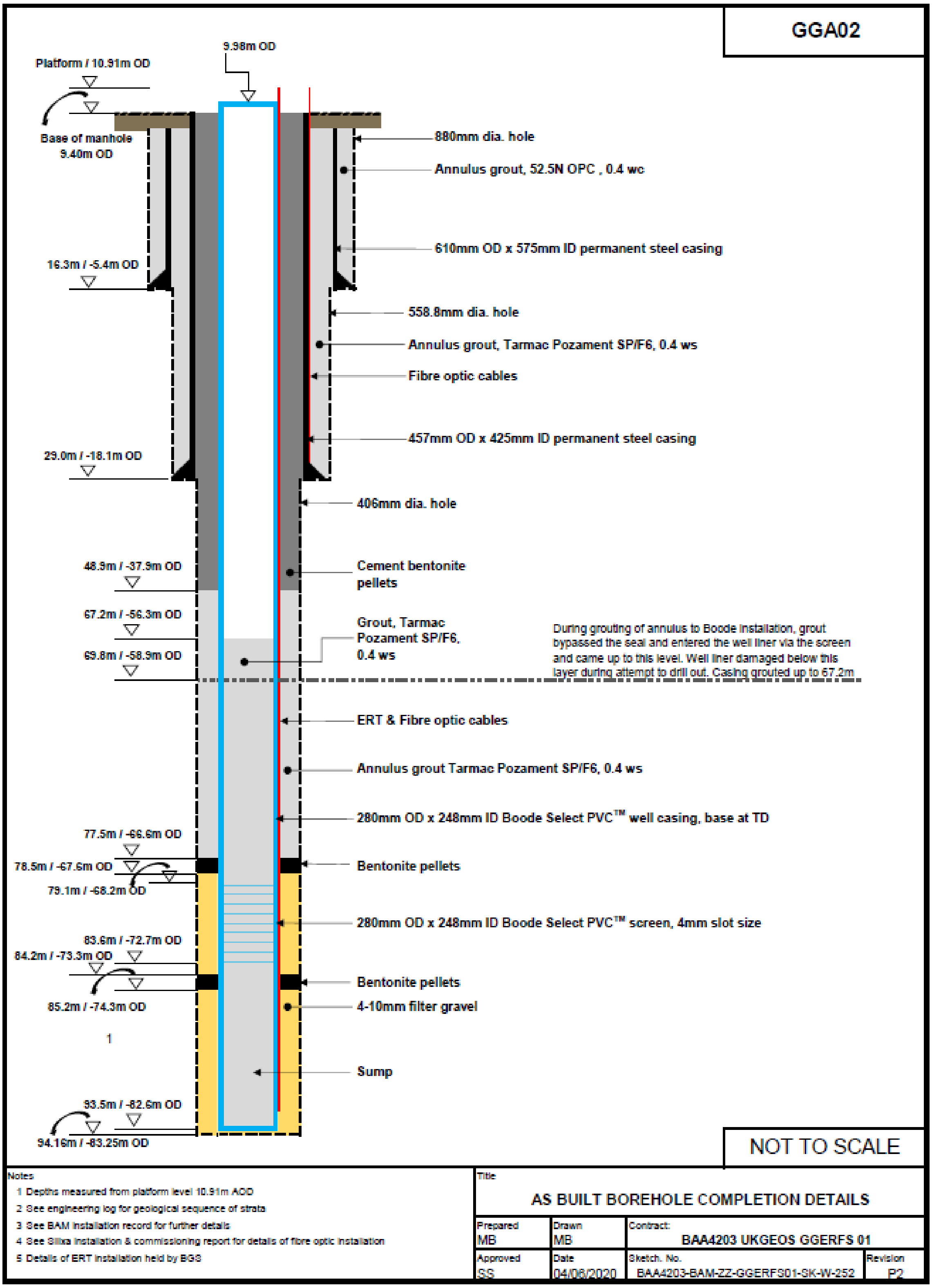


Figure 4 As-built borehole schematic for GGA02

2.1 BASIS OF DESIGN

The basis of the GGA02 borehole design was as follows;

i. Separate borehole casings were installed through the made ground, superficial deposits and bedrock sections of all the UK Geoenergy Observatory boreholes at Cuningar Loop, with the annulus of the different casing sections grouted before the next section was drilled. This was done to prevent the mixing of groundwaters of different quality, which could occur if vertical flow paths were created during drilling (important to avoid from both an environmental quality and scientific research perspective).
ii. Additional measures were planned to be taken during drilling to prevent the mixing of waters from different mine workings, as a precaution in case the Glasgow Upper, Ell and Main workings were later found to be hydraulically isolated. This was necessary to preserve the in-situ conditions for scientific research, and to minimise any environmental impact should one mine working contain water of much poorer quality. In order to achieve this, the Glasgow Upper and Glasgow Ell mine workings were sealed with a plug of grout as they were encountered, and then the centre of these plugs were drilled though as the borehole progressed downwards to the Glasgow Main mine working target.
iii. The borehole is screened only across the target interval (the zone thought to contain the collapsed Glasgow Main mine working) and is fully sealed above the screen, so that all hydrogeological observations from this borehole relate only to this interval.
iv. The large internal diameter of the bedrock casing and slotted screen section of borehole GGA02 (248 mm ID) was chosen to accommodate a large borehole pump capable of delivering a high flow rate.
v. A screen slot size of 4 mm was used with a 4 – 10 mm sized filter gravel filling the sump and annulus around the screened section.
vi. A sump section was included in the borehole design to accommodate the termination unit of the fibre optic sensor cables (see below) and to catch any fines that enter through the slotted screen.
vii. Bentonite seals were used in the annulus above and below the screened section at 77.5 – 78.5 mbgl and 84.2 – 85.2 mbgl.
viii. The annulus was grouted with a SP/F6 mix. Unfortunately, as described in section 3, grout entered the inside of the casing, cementing up the screened section and resulting in GGA02 becoming a sensor testing borehole.

Table 3 Summary of heights for key as-built borehole features for GGA02

Feature	Depths (drill length from drill platform level, metres)	Height (m) relative to Ordnance Datum	As-built length (m) down hole from top casing datum (top Boode flange)
Final completion depth (top grout)	67.2	-56.29	66.27
Top slotted screen – *not accessible due to grout ingress*	79.10	-68.19	78.17
Base slotted screen – *not accessible due to grout ingress*	83.60	-72.69	82.67
Base installed casing sump – *not accessible due to grout ingress*	93.5	-82.59	92.57
ERT sensor positions	See Table 5 below	Not shown	See Table 5 below
Position of DTS termination unit – superficial casing	Termination unit depth: 28.7	Termination unit depth: -17.79	Termination unit depth: 27.77
Position of DTS termination unit – bedrock casing	Termination unit depth: 93.0 Working cable: 0 - 72.65	Termination unit depth: -82.09 Working cable: 10.91 – -60.82	Termination unit depth: 92.07 Working cable: 0 – 71.72

3 Drilling, casing, annulus grouting and testing methodology

Borehole GGA02 was drilled and cased in separate sections for made ground, superficial deposits and bedrock. The drill rig moved off to complete sections of other boreholes on site a number of times, thus the overall timescale for the borehole appears much longer than would be expected (Tables 1, 4).

Table 4 summarises the steps involved in the drilling of GGA02, further details are given in the borehole information summary at the end of the Drillers' log file (see section 4.1). Other points of note include

- Water flush was used throughout the drilling of the superficial deposits and bedrock sections
- The drilling technique in the made ground section was piling rig with auger. In the superficial deposits and bedrock sections rotary open hole with reverse circulation was used.
- Fluid and rock chip samples were taken from the superficial deposits and bedrock sections for academic researchers and rock chip samples were taken for archiving in the BGS National Geological Repository.
- As described in section 2, the Glasgow Upper and Glasgow Ell mine workings were grouted and sealed before proceeding to the Glasgow Main mine working to prevent a pathway being created between the mine workings.

Table 4 Summary of drilling, casing, grouting and testing. All depths are in metres below drilling platform level (mbgl).

Drilling and installation summary:	
17/06/2019	Drilled and installed made ground and superficial casing with piling rig to 16.0 mbgl, with a 34 ¾" (880 mm) auger. Base made ground level was recorded at 9.5 mbgl
18/06/2019	Made ground and superficial casing annulus grouted. Casing was installed to 16.3 mbgl due to sinking into superficial deposits
16/07/2019 – 17/07/2019	Drilled superficial deposits to rockhead with Fraste rig from 16.0 mbgl to 30.2 mbgl, with a 22" (558.8 mm) tri-cone bit Rockhead encountered at 27.0 mbgl **Problems Encountered:** Some hole instability
18/07/2019 – 19/07/2019	Steel casing was installed to 29.0 mbgl for the superficial deposits. Installation of fibre optic cables on the outside of the steel casing by Silixa on 18/07/2019 – casing stabiliser was welded on to the casing (Figure 5) The casing annulus was grouted on 19/07/2019 – after completion of grouting, Silixa tested the fibre optic cables – installation successful
24/07/2019 – 25/07/2019	Drilled to Glasgow Upper mine working with Fraste rig from 30.2 to 49.0 mbgl with a 16" (406 mm) tri-cone bit The Glasgow Upper was encountered as packed waste from 47.8 – 48.95 mbgl Drilling indications included faster drilling and increased volume of cuttings return at the shakers – cuttings returns were mainly coal and sandstone with some small fragments of wood a few cm long – towards the base of the working some sticky light grey clay returned

Drilling and installation summary:	
25/07/2019	Borehole purged (cleaned) using air lift to obtain groundwater sample representative of Glasgow Upper mine working – 22 m^3 was removed in 15 mins. Water samples were taken by BAM and BGS – the groundwater is likely to have come from the mine working, but some may also have come from the overlying sandstone exposed in the open borehole
26/07/2019	A second groundwater sample was taken by BAM and BGS using a discrete sampler at the Glasgow Upper mine working level A downhole camera was used to attempt to view the mine working but did not produce a usable image due to suspended sediment Grouting of Glasgow Upper mine working commenced, with monitoring of grout volumes and levels in the borehole
29/07/2019	On monitoring the grout volumes and height risen up in the borehole, the drilling contractors concluded that due to the packed nature of the mine waste the grout had not penetrated sufficiently into the working to create a plug of suitable diameter. This could result in the grout cracking once drilling commenced and the Glasgow Upper mine working would not be isolated from the other workings thus compromising the requirements of SEPA and BGS. Drilled out grout from 32.5 to 50.0 mbgl
30/07/2019 – 01/08/2019	Creation of 12 m sump to a depth of 62.0 mbgl and jetting of mine working interval to create space for grout plug of suitable diameter to seal mine working – second attempt at grouting Glasgow Upper mine working and sump considered successful
02/08/2019 – 05/08/2019	Drilled through grout plug and continued to Glasgow Ell, from 48.3 to 71.3 mbgl with a 16” (406 mm) tri-cone bit The Glasgow Ell mine working encountered as a water-filled void from 70.16 to 70.76 mbgl – main indications of the void were the rapid drop of the drill string and lack of returns at the shaker, plus a strong smell of H_2S
06/08/2019 – 14/08/2019	Grouting of the Glasgow Ell mine working • Pea gravel and grout mix (SP/F6) was used • Tagged and attempted to drill out grout - only gravel was being returned and no grout present • Consultation with Science Advisory Group as to whether to complete borehole across Glasgow Ell mine working. Decision was to proceed with grouting • Second grout attempt on Glasgow Ell void, Blue Circle procem cement – tagged after 1 day, more added to bring above level of working, however further tagging suggested this had not sealed the void • Continued attempts of grouting and tagging level, Trojan grout used • Rig moved off to drill borehole GGA03r
20/08/2019	Optical and acoustic televiewer down borehole showing a void of 20 cm present at the top of the Glasgow Ell mine working. Inappropriate stabilisers for televiewer and the wide borehole diameter resulted in poor quality images (not released as open data)
22/08/2019 – 23/08/2019	Final grouting attempt on Glasgow Ell void using NuGrout tagged at 67.85 mbgl deemed as sufficient indication that the mine working had successfully been sealed
26/08/2019	Drilled out grout at Glasgow Ell and continued towards Glasgow Main mine working, from 65.8 to 73.0 mbgl with a 16” (406 mm) tri-cone bit – drilling paused and rig moved to a different borehole due to awaiting fibre optic cables

Drilling and installation summary:	
17/09/2019 – 19/09/2019	Continued to Glasgow Main target, from 73.0 to 94.16 mbgl, with a 16” (406 mm) tri-cone bit – Glasgow Main mine working not confidently identified from drilling response or returns – most likely a fully collapsed mine working at around 82 – 83m (see section 7) **Problems Encountered:** drill rod snapped at centraliser downhole at approx. 86.0 mbgl
20/09/2019	Casing installation with fibre optic and ERT cables attached on to exterior of casing • The target section between 79.10 – 83.60 mbgl screened with 4 mm slotted Boode casing • Casing depth 93.5 mbgl, leaving 0.66 m open hole to be filled with gravel
23/09/2019	Installation of gravel and lower and upper bentonite seals between casing and rock wall – bentonite left to swell/set before grouting • Gravel added to the base of the borehole • 1m bentonite plug was installed at 84.2 – 85.2 mbgl and gravel added to the annulus of the screened section • Second 1m thick bentonite plug placed at 77.5 – 78.5 mbgl above the screened section
24/09/2019	Grouted borehole annulus with SPF6 grout installed via tremie pipe. Silixa tested fibre optic cable – functioning correctly
25/09/2019	Checking the inside the casing revealed grout in casing to a depth of 69.8 mbgl, with grout across the target/ screened interval – attempted to rescue borehole via drilling out partially hardened grout. • Grout drilling abandoned after chips of Boode casing returned • Borehole annulus grout level was tagged at 52.8 mbgl, suggesting that around 40% of the grout added is unaccounted for – contractors suggest it has gone into the formation • Rig moved off hole on 26/09/2019 to another borehole until decision made on how to proceed
08/10/2019 – 11/10/2019	• Set up submersible pump • Water pumped out of borehole to allow camera to survey GGA02 • The survey was not conclusive but strongly suggested that the Boode (bedrock) casing was damaged (perforated) at c. 72 mbgl during grout drilling. • Silixa tested the fibre optic cable and identified damage at approx. 72.5 m – not be possible to run the ‘bedrock’ fibre optic cable in active heating mode • ERT cable undamaged
25/10/2019 – 05/11/2019	Grouting remainder of annulus in stages
09/01/2020	Cased hole logs run by Robertsons Geo Services
12/11/2019	Inside of Boode casing grouted to 67.2 mbgl, above area of perforation of casing

The mechanism by which annulus grout entered the inside of the borehole casing on 24–25/09/2019 and filled it to a level above the screened section is uncertain. It is hypothesised that the grout entered inside the casing through the screened section, but whether a pathway to the screened section resulted from failure of the bentonite seal and grout flow down the borehole annulus, or whether grout flow was via linked vertical and horizontal fractures in the rock mass from above the bentonite seal to the screened section, remains a matter of debate. A lesson learnt during the construction of this borehole was that gaining a good quality optical or acoustic camera image of the mine working zone would have reduced uncertainties in the location of any collapsed mine working and in fracture systems that would influence placement of the seal. Obtaining a good quality camera image requires >24 hour drill rig down time to both clean/purge the borehole and let suspended sediment settle and so has cost implications.

3.1 SENSORS INSTALLED

3.1.1 Electrical resistivity tomography (ERT) downhole sensors

Electrical resistivity tomography (ERT) is a geophysical technique that uses electrode arrays to profile the electrical resistivity of the subsurface. At UKGEOS Glasgow electrode cables were deployed in the six mine water characterisation boreholes to facilitate cross-borehole imaging of geoelectrical properties and the automated remote 4D monitoring of natural and induced changes in subsurface conditions.

ERT Installation

An ERT cable was fastened to the outside of the Boode well casing, including across the screened section, and the casing and cables were then lowered into the borehole (Figure 4, Table 5). Two ERT cables were installed on the casing to provide full depth coverage. The cables are designed to be connected to the same measurement instrument so that all of the deployed sensors can be used as part of the same measurement scheme. When the casing and cables had been installed, the annulus between the casing and rock wall was grouted above the screened section to seal in the casing and provide a good electrical connection between the ERT electrodes and the surrounding formation. Appendix B provides a more detailed description of the installation method for the ERT and fibre-optic cables.

Output Data

The data will be measured by a BGS-designed system known as PRIME, which connects multiple ERT electrodes to a common control unit so that the resistivity between various electrode pairs can be continuously scanned. The PRIME system is operated remotely and designed for minimum on-site intervention. All acquisition strategy design, measurement scheduling and data download will be undertaken remotely via a secure 3G/4G Wireless internet link.

Table 5 Position of the ERT sensors relative to drilling platform and as-built datums

Drill platform datum level (m AOD)		10.91	
As-built datum level at top casing flange (m AOD)		9.98	
Electrode number Cable 1	**Electrode number Cable 2**	**Depth below drill platform datum (m)**	**Depth below as-built casing flange datum (m)**
32		32.85	31.92
31		33.59	32.66
30		34.34	33.41
29		35.08	34.15
28		35.82	34.89
27		36.56	35.63
26		37.31	36.38
25		38.05	37.12
24		38.79	37.86
23		39.53	38.60
22		40.28	39.35
21		41.02	40.09
20		41.76	40.83
19		42.50	41.57
18		43.25	42.32
17		43.99	43.06
16		44.73	43.80
15		45.47	44.54
14		46.22	45.29
13		46.96	46.03
12		47.70	46.77
11		48.44	47.51
10		49.19	48.26
9		49.93	49.00
8		50.67	49.74
7		51.42	50.49
6		52.16	51.22
5		52.90	51.97
4		53.64	52.71
3		54.39	53.46
2		55.13	54.20
1		55.87	54.94
	40	56.61	55.68
	39	57.36	56.43
	38	58.10	57.17
	37	58.84	57.91
	36	59.58	58.65
	35	60.33	59.40
	34	61.07	60.14
	33	61.81	60.88
	32	62.55	61.62
	31	63.30	62.37

	30	64.04	63.11
	29	64.78	63.85
	28	65.52	64.59
	27	66.27	65.34
	26	67.01	66.08
	25	67.75	66.82
	24	68.50	67.56
	23	69.24	68.31
	22	69.98	69.05
	21	70.72	69.79
	20	71.47	70.54
	19	72.21	71.28
	18	72.95	72.02
	17	73.69	72.76
	16	74.44	73.51
	15	75.18	74.25
	14	75.92	74.99
	13	76.66	75.73
	12	77.41	76.48
	11	78.15	77.22
	10	78.89	77.96
	9	79.63	78.70
	8	80.38	79.45
	7	81.12	80.19
	6	81.86	80.93
	5	82.60	81.67
	4	83.35	82.42
	3	84.09	83.16
	2	84.83	83.90
	1	85.58	84.65

3.1.2 Fibre-optic cables (FO)

The fibre-optic cables installed within the borehole are optoelectronic devices that can act as series of "distributed temperature sensors" (DTS) to produce a continuous profile of in-situ temperature along the cable. When an interrogator box is connected to the top of the cable, a pulsed laser signal propagates through the fibre-optic cable and measurements of the temperature-dependent backscatter are recorded. In passive mode DTS monitors in-situ temperature variation and can be used, for example, to infer flow pattern from naturally occurring thermal anomalies. The fibre-optic cables also have the ability to measure distributed acoustics should an iDAS interrogator box be connected.

The cables installed into the Glasgow mine water boreholes are all active DTS and so include a copper element, which can be used to generate a heat pulse. The decay of this heat pulse can be monitored using the DTS fibre and used to infer the presence of flow zones, or regions of increased thermal conductivity.

FIBRE-OPTIC CABLE INSTALLATION

GGA02 fibre-optic cable installation was different to the other mine water boreholes in that an additional section of cable was installed on the outside of the steel superficial deposits casing (Figure 5) prior to grouting the annulus. The termination unit was installed at a depth of 28.97 m below the drilling platform level.

Figure 5 Photograph of the bottom section of the steel superficial deposits casing with fibre-optic cable attached and welded centraliser, during installation at GGA02 on 18/07/2019

A second DTS fibre-optic cable was fastened on to the outside of the Boode well casing, across the screened section and terminating at a depth of 93 m. The termination unit of the FO cable was installed below the first ERT sensor to ensure that the metal of the unit did not interfere with the ERT signal. Once installed, the section was grouted between the casing and rock wall and around the cable. Appendix B provides a more detailed description of the installation method for the ERT and the fibre optic cables, along with the contractors reports included in the information release [*FibreOpticCableBedrock Installation Report BGS V1.3 GGA02 11 260520.pdf* and *FibreOpticCableSuperficial Installation Report BGS V1.2 GGA02 18 26052020.pdf*].

Installation depths of cables and the termination unit are shown in Table 3 above.

During the attempt to remove the grout that had ingressed into the cased section of the borehole (Table 4), the Boode casing and attached fibre-optic cable was damaged. The result is that the fibre optic cables across the Boode casing can be used to a depth of 72.65 m below drill platform level but will only work in the single ended configuration mode providing one-way measurements. The copper wires cannot be used to heat the cable thus restricting the use of the fibre-optics to a passive mode only. The fibre-optic cables across the superficial deposits can be used both in the active and passive modes.

OUTPUT DATA

The passive DTS cables are used in conjunction with a DTS interrogator box, which generates the light signal and interprets the signal return. For use of the active DTS system a separate heat pulse control unit is also needed.

3.1.3 Hydrogeological data logger

A data logger was not installed in GGA02.

4 Borehole logs

4.1 DRILLERS' LOG

The drilling contractors log is included in the data pack [*Drillers_Log_GGA02.pdf*]. This is a record of the lithologies encountered, as recorded on-site by the drillers. Apart from the upper part of the made ground section which is based on trial pits, this log was not recorded by a geotechnical engineer. Due to the nature of the drillers' log, there are differences between it and BGS rock chip log (Section 4.2).

The borehole information summary sheets at the end of the driller's log record the drilling progress each day, casing sizes, flush type used etc. All eleven drillers' logs for UKGEOS boreholes at Cuningar Loop have been exported by the drilling contractor to the file *UKGEOSCuningar_BAA4203_FinalAGS.AGS* in the Association of Geotechnical Specialists standard text file format.

4.2 BGS ROCK CHIP LOG

BGS geologists were on site during borehole drilling to collect samples, record a field lithological log and to make decisions based on this log, such as the positioning of borehole screens and seals. A one litre tub of rock chips from the open hole drilling was generally taken every metre, to be representative of the lithologies encountered in that metre. Other notable features such as the top and base depths of key intervals such as coals and mine workings were recorded in discussion with the drillers.

Subsequently, the rock chip tubs were transported to BGS Edinburgh. Tubs containing unconsolidated superficial deposits were placed in a cold store. Rock chip tubs were dried and logged by BGS geologists working in a laboratory with the aid of a microscope.

The resulting lithological log record [*Detailed_BGS_Rockchiplog_GGA02.pdf and .xlsx*] gives the percentage of lithologies returned as rock chips within the 'metre' tub, with some sedimentological characteristics. The dictionaries controlling the majority of the fields are provided via the tab on the spreadsheet. A sedimentological scheme was used to describe the lithologies to facilitate comparison with core logging of UKGEOS borehole GGC01:

- The Udden-Wentworth grain size scale was used
- With initial logging taking place at drill site, a classification level of mud/mudstone, sand/sandstone and gravel was used. Following the hierarchy of the BGS Rock

Classification Scheme (Hallsworth and Knox, 1999), subsequent logging in the laboratory subdivided mud/mudstone to clay and silt, and to the sandstone grain sizes (fine, medium etc) and the gravel to granule and pebble grades. Percentages on the graphic logs are given at the mud/mudstone and sand/sandstone classification level. Detail on clay/silt etc is given in the descriptive field in the BGS rock chip log.

- Grain sizes, angularity, sorting and percentages etc were referred from a standard grain size card based on Tucker (2011).
- Logging was not based on ISO 14688-1:2002 (geotechnical engineering standard)

5 Wireline (geophysical) downhole data

Wireline logging or geophysical logging is the process of measuring the properties of geological units using sensors attached to a winch cable (wireline) suspended in the borehole. Measurements are made continuously down the borehole by raising or lowering the sensor tools. The property measurements are then converted to a standard series of geophysical logs.

5.1 ACQUISITION

The wireline logs were acquired by Robertson Geo Services. They were acquired as cased hole logs which refers to the fact that the tools were run after the Boode casing had been installed and grouting of the annulus had been completed. Information about the tools and their associated certification is located within the report '*Wireline Logging Report for UKGEOS Glasgow Conducted by Robertson Geo Ltd On behalf of BGS 9/1/20 -----10/1/20'* included in the information release [*BAM Nuttall Glasgow Report Final.pdf*].

5.2 SUMMARY AND OUTPUTS

The following wireline logs were run within Borehole GGA02 (Table 6)

Table 6 Cased hole wireline logs run for GGA02. All downhole depths in the released datasets were measured from the drill platform depth 10.91 m.

Wireline Log	Depth below drill platform level (10.91 m AOD)	Depth below final datum (top casing) (9.98 m AOD)
Gamma cased hole	3.3 – 65.58	2.37 – 64.65
Caliper cased hole	3.3 – 65.58	2.37 – 64.65
Inclination cased hole	3.3 – 65.58	2.37 – 64.65
Azimuth cased hole	3.3 – 65.58	2.37 – 64.65
Cement Bond Log	20 – 65.58	19.07 – 64.65

Wireline logs were output in the following formats:

1. PDF

PDF files showing all of the logs are included [*Cased_hole_GGA02_BoreholeGeometry.pdf* and *Cased_hole_GGA02_CementBondLog.pdf*]. The header data provides information about the borehole location, the drilling datum and the casing and drill depths of each section. Note that all depths on the logs are based on the drill platform datum.

2. LAS

Conventional geophysical logs are provided in LAS format [*Cased_hole_GGA02_BoreholeGeometry.las* and *Cased_hole_GGA02_CementBondLog.las]*. This is a column separated ASCII format. Almost all specialist logging software is capable of loading and interpreting geophysical log data in LAS format. In addition to this LAS files can also be viewed in any software capable of manipulating an ASCII text file, including Notepad (Windows), VI (Unix) or spreadsheets (e.g. Microsoft Excel).

5.2.1 Problems and caveats with the wireline logs

BGS reviewed the data and made minor comments primarily relating to the header information and the scale used in the .pdf files. No editing has been done on any of the logs.

The caliper log indicates a constant separation between the X and Y readings. This is related to the probe leaning to one side of the borehole. The probe is quite heavy and even with centralisers, it can tilt/lean to one direction. This means the calipers may not read identical even in a perfectly round casing. It does not indicate an oval casing shape.

The borehole is roughly vertical (inclination less than 2 degrees) and undeviated. The borehole azimuth log shows a lot of variation between 0 and 360 degrees because of very slight changes in direction from the vertical.

The cement bond log [*Cased_hole_GGA02_CementBondLog.pdf*] only records useful data when the sensor is below water level. For borehole GGA02, the water level was 26.8 m at the time of the wireline logging, so the valid data is between 26.8 – 65.58 m. The log has not been edited or changed from the data sent by Robertson Geo Services.

6 Archived rock chip samples

Section 4.2 describes how representative one litre tubs of rock chips were taken every metre during open hole drilling. These samples have been archived in the National Geological Repository at BGS Keyworth for future research. The data pack includes a spreadsheet summarising the rock chip tubs available [*GGA02_archived_rock_chips.xlsx*]. For the composition of the samples refer to the BGS rock chip log [*Detailed_BGS_Rockchiplog_GGA02.pdf and .xlsx*].

During-drilling fluid and rock chip samples were also supplied to a number of University groups for their ongoing research. Data from that research will be returned to NERC/BGS data centre and made publically available on a 2 year timescale.

7 Initial geological interpretation

Integration of drillers' information, rock chip logs and wireline log data together with correlation to legacy borehole and mine plan data has allowed an initial geological interpretation of borehole GGA02 (Figure 1).

The made ground composition including brickwork, wood, ash, cementwork etc. is as expected from legacy data nearby and the prior land use history as a site where housing demolition rubble was disposed of. The thickness of the made ground at 9.5 m was less than the pre-drill prognosis (Appendix C), though compatible with a complex and variable anthropogenic deposit.

The superficial deposits are interpreted as a Quaternary age succession of glacial and post-glacial deposits, following existing legacy interpretations and geological models (e.g. Arkley, 2019). A preliminary interpretation comprises sand, gravel and clay of the alluvial Gourock Sand Member to around 15.4m, with clay with sand and gravel of the raised marine Paisley Clay Member to around 22 m drilled depth (Figure 1). Underlying sand and gravel could represent glaciofluvial deposits of the Broomhouse Sand and Gravel Formation with a gravel, sand and silt unit logged between 26 – 27 m drilled depth interpreted as a sandy glacial diamicton (till) of the Wilderness Till Formation (Figure 1). Rockhead was recognised between 26 – 27 m drilled depth, within error limits of the pre-drill prognosis (Appendix C).

The bedrock succession appears typical of the Scottish Middle Coal Measures Formation. The *c.*20 m section of sandstone with thin coal, siltstone and claystone interbeds above the Glasgow Upper mine working is more sandstone dominant compared to nearby legacy and UKGEOS boreholes (e.g. GGC01 cored borehole, Kearsey et al. 2019). The *c.*21 m clay- and siltstone-dominated Glasgow Upper to Glasgow Ell section and the interbedded sandstone, siltstone, claystone and coal section from the Glasgow Ell to below the Glasgow Main appear typical, with the exception that a Glasgow Main coal seam or mine working was not recognised at the expected position.

7.1 MINE WORKINGS

The ***Glasgow Upper mine working*** was recognised by faster drilling rate and increased volume of rock chips returned, mainly coal and sandstone with some small fragments of wood, indicating a mining waste. Together with hydrogeological indications from air-lift purging for water sampling ($22m^3$ in 15 minutes), the > 1m height of the working and the observations from grouting the waste (Table 4), the interpretation is of a loose to moderately packed mine waste. Permeability may decrease towards the base of the waste as returns of a light grey clay, typical of the floor of the Glasgow Upper coal were returned towards the base. This interpretation is compatible with mine abandonment plans[*] which record total extraction of this area at 1928 (on 1933 plan) following earlier irregular-shaped worked areas and access roads (elongate stoop and room; 1884 plan). The depth of the mineworking is 47.8 – 48.95 mbgl drilled depth is as expected from mine plan spot heights and legacy boreholes nearby and within the ±4 m error limits of the pre-drill prognosis (Appendix C). The 1.15 m thickness of the Glasgow Upper mine working recorded proved to be one of the thinnest Glasgow Upper mine workings or intact coal recorded in the UKGEOS boreholes.

The ***Glasgow Ell mine working*** was recognised by a rapid drop of the drill string and lack of returns at the shaker, along with a strong smell of hydrogen sulphide and is interpreted as a water-filled void from 70.16 to 70.76 mbgl drilled depth. This interpretation is compatible with a mine abandonment plan (1933) which records total extraction in this area with dates of November 1923 and March 1926 nearby. The drilled depth of the Ell mineworking in GGA02 was shallower than on the pre-drill prognosis from a semi-regional model (Appendix C), though compatible with mine spot height value of -58.5 m relative to OD 30 m away (808.05 ft rel colliery datum/equates to 69.4 m drill length). The 0.7 m thickness of the void is smaller than the *c.*1.2+ m coal thickness summarised on the mine abandonment plan (1933) and *c*1.4 m Glasgow Ell coal thickness in GGC01 (Kearsey et al., 2019), suggesting some collapse of the mine working.

The mine abandonment plans for the ***Glasgow Main mine working*** record total extraction of the area around GGA02 at 1924 and 1928. GGA02 is within 15 m of a number of former access routes and 50 m from a spot height of -74.9 m rel OD (749.89 ft rel colliery datum/equates to 85.8 m drill length) and worked thicknesses of 24 – 36 inches (0.6 m – 0.9 m). Therefore, the presence and depth of the mine working is well constrained, however the mine working was not recognised during on drilling of GGA02.

---

[*] Mine abandonment plan scans available from The Coal Authority

Over the interval where the mine working was expected based on the mine plan information, the drill rod response could have indicated fracturing in sandstones around 82 – 86 mbgl drilled depth (however at 86 m a drill rod centraliser failed, so this is not a reliable indicator) and there were traces of iron-staining and coal between 81– 83 mbgl drilled depth. The lithological succession appeared fairly typical of the Glasgow Ell to Glasgow Main interval, and below the Glasgow Main interval to 94.16 m drilled depth, but with the coal seam and mine working missing in the expected position based on the lithological sequence and mine plan at around 82 – 83 m drilled depth. Taking all this into account, the interpretation is that the sandstone roof had completely and cleanly collapsed on a sandstone floor at around 82 – 83 m drilled depth, resulting in the Glasgow Main mine working not being recognised on drilling.

8 References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

Datasets are available at https://www.ukgeos.ac.uk/data-downloads

ARKLEY, S. 2018. Model metadata report for the Glasgow Geothermal Energy Research Field Site superficial deposits model. *British Geological Survey Open Report*, Nottingham, UK, OR/18/064, 50pp. http://nora.nerc.ac.uk/id/eprint/524556/

BURKIN, J, and KEARSEY, T. 2019. Model metadata report for Glasgow Geothermal Energy Research Field Site bedrock model. *British Geological Survey Open Report* Nottingham, UK, OR/18/053, 18pp. http://nora.nerc.ac.uk/id/eprint/522737/

HALLSWORTH, C R, and KNOX, R W O'B. 1999. BGS Rock Classification Scheme Volume 3. Classification of sediments and sedimentary rocks. *British Geological Survey Research Report*, RR 99-03.

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, Nottingham, UK, 36pp. http://nora.nerc.ac.uk/id/eprint/525009/

MONAGHAN, A A, Ó DOCHARTAIGH, B E, FORDYCE, F M, LOVELESS, S, ENTWISLE, D, QUINN, M, SMITH, K, ELLEN, R, ARKLEY, S, KEARSEY, T, CAMPBELL, S D G, FELLGETT, M, and MOSCA, I. 2017. UKGEOS: Glasgow Geothermal Energy Research Field Site (GGERFS): initial summary of the geological platform. Nottingham, UK, *British Geological Survey Open Report,* OR/17/006. http://nora.nerc.ac.uk/id/eprint/518636/

MONAGHAN, A A, STARCHER, V, Ó DOCHARTAIGH, B E, SHORTER, K M, and BURKIN, J. 2019. UK Geoenergy Observatories: Glasgow Geothermal Energy Research Field Site: Science Infrastructure Version 2. Nottingham, UK, *British Geological Survey Open Report*, OR/19/032 http://nora.nerc.ac.uk/id/eprint/522814/

TUCKER, M E. 2011. Sedimentary Rocks in the Field: A Practical Guide (Geological Field Guide) 4th edition, Wiley-Blackwell 288pp ISBN: 978-0-470-68916-5

Appendix A: Summary of borehole GGA02 files in this information release

Table 7 Summary of files in the borehole GGA02 information release

Description	File name	File type
BAM Drillers log – an engineering format log with lithological information as recorded on drill site by the drilling contractor (not a geotechnical engineer). *NOTE: depths are given relative to drill platform level*	Drillers_Log_GGA02.pdf UKGEOSCuningar_BAA4203_FinalAGS.AGS *(this covers all 11 UKGEOS boreholes at Cuningar Loop)*	PDF AGS format
BGS log- detailed. A log recording the percentage of different lithologies returned as rock chips during the open hole drilling on a metre by metre basis. Included as a spreadsheet and a visualisation plot. *NOTE: depths are given relative to drill platform level*	Detailed_BGS_Rockchiplog_GGA02.pdf Detailed_BGS_Rockchiplog_GGA01.xlsx	XLSX, PDF
BGS summary log – a 1 or 2 page visualisation of the BGS log and summary interpretation. *NOTE: depths are given relative to drill platform level*	Summary_BGS_Log_Page1_GGA02.pdf Summary_BGS_Log_Page2_GGA02.pdf	PDF
Wireline (geophysical) downhole data for cased hole logs *NOTE: depths are given relative to drill platform level*	Cased_hole_GGA02_BoreholeGeometry.pdf and .las Cased_hole_GGA02_CementBondLog.pdf and .las BAM Nuttall Glasgow Report Final.pdf 'Wireline Logging Report for UKGEOS Glasgow Conducted by Robertson Geo Ltd On behalf of BGS 9/1/20 – 10/1/20.pdf'	.las, PDF
Fibre optic cable installation reports	FibreOpticCableBedrock Installation Report BGS V1.3 GGA02 11 260520.pdf and FibreOpticCableSuperficial Installation Report BGS V1.2 GGA02 18 26052020.pdf	PDF
Spreadsheet of archived rock chip samples *NOTE: depths are given relative to drill platform level*	GGA02_archived_rock_chips.xlsx	XLSX

Appendix B: Detailed installation method for ERT and DTS cables

The installation of the fibre-optic cable in the superficial deposits followed an identical process to that of the deployment of fibre-optic cable within the bedrock section. The following text describes the installation method adopted for the deeper section which also involved the attachment of the ERT sensors to the casing string.

The two ERT cables with attached sensors were loaded onto a cable reel and passed over a sheave wheel which was mounted at an elevation of approximately 3 m. The fibre optic cable was loaded onto a separate cable reel and also passed over the sheave wheel. It was ensured that neither cable dragged on the floor or caught on any other equipment. Both the steel casing through the superficial deposits section and the Boode well casing was measured from bottom to top edge of the exposed outer surface without the inclusion of the threaded joining sections. The Boode casing length was in the order of 0.9 m per section. Based on borehole installation information including length of screen, desired annulus seal location and length of sump, the nominal positions of the ERT electrodes and fibre-optic cable centralisers was marked onto the casing.

The casing section to be installed was winched into a vertical position at a working height above the borehole. The fibre-optic bottom hole assembly (BHA) was placed onto the casing and fastened into position. This was wrapped in duct tape to protect the equipment as it moved down the borehole. The dead end seal of the first ERT cable was attached above the BHA of the fibre-optics and the first sensor was fastened onto the casing in the marked location. The ERT electrode and fibre-optic cable was secured in place with cable ties and duct tape. The casing was lowered into the borehole and the cables were guided through the centralisers. The next casing string was hoisted into the vertical position and the attachment of sensors resumed.

The screened section had sensors attached directly to it and the cables had to pass through the fins of the rubber seal. The two cables were fastened to the seal with cable ties and jubilee clips and then taped tightly to ensure that there were no loose ends.

Once all of the sensors were in place, the remaining cable was spooled off and the cables within the borehole were tested. Both the ERT cable ends and the fibre-optic cable end were protected from moisture, water ingress and dirt by placing them into a sealed bag and placing into a dry and secure box.

Subsequently the annulus of the borehole was grouted between the casing and rock wall and around the cables.

The cabinets with the data recording equipment (PRIME for the ERT and DTS interrogation box for the fibre optics) were installed at a later date.

Appendix C Pre-drill borehole prognosis

The pre-drill borehole prognosis (Figure 6) was produced from semi-regional superficial deposits, bedrock and mine 3D geological models (Arkley, 2019; Burkin and Kearsey, 2019) and legacy boreholes nearby. The prognoses were used in planning the depth, spacing and design of the boreholes and were indicative of the likely unit depths to be encountered. As the prognoses were not based on detailed site specific interpretations, the uncertainty and error values were understood to be quite large.

The pre-drill borehole prognoses as shown in Figure 6 were updated on paper at site during the drilling phase, for example the confirmed depth of the Glasgow Upper mine working in GGA02 informed the expected depth of GGA01 Glasgow Upper mine working. Being the pre-drill information, Figure 6 does not represent the learnings or local, site specific considerations used during the drilling phase.

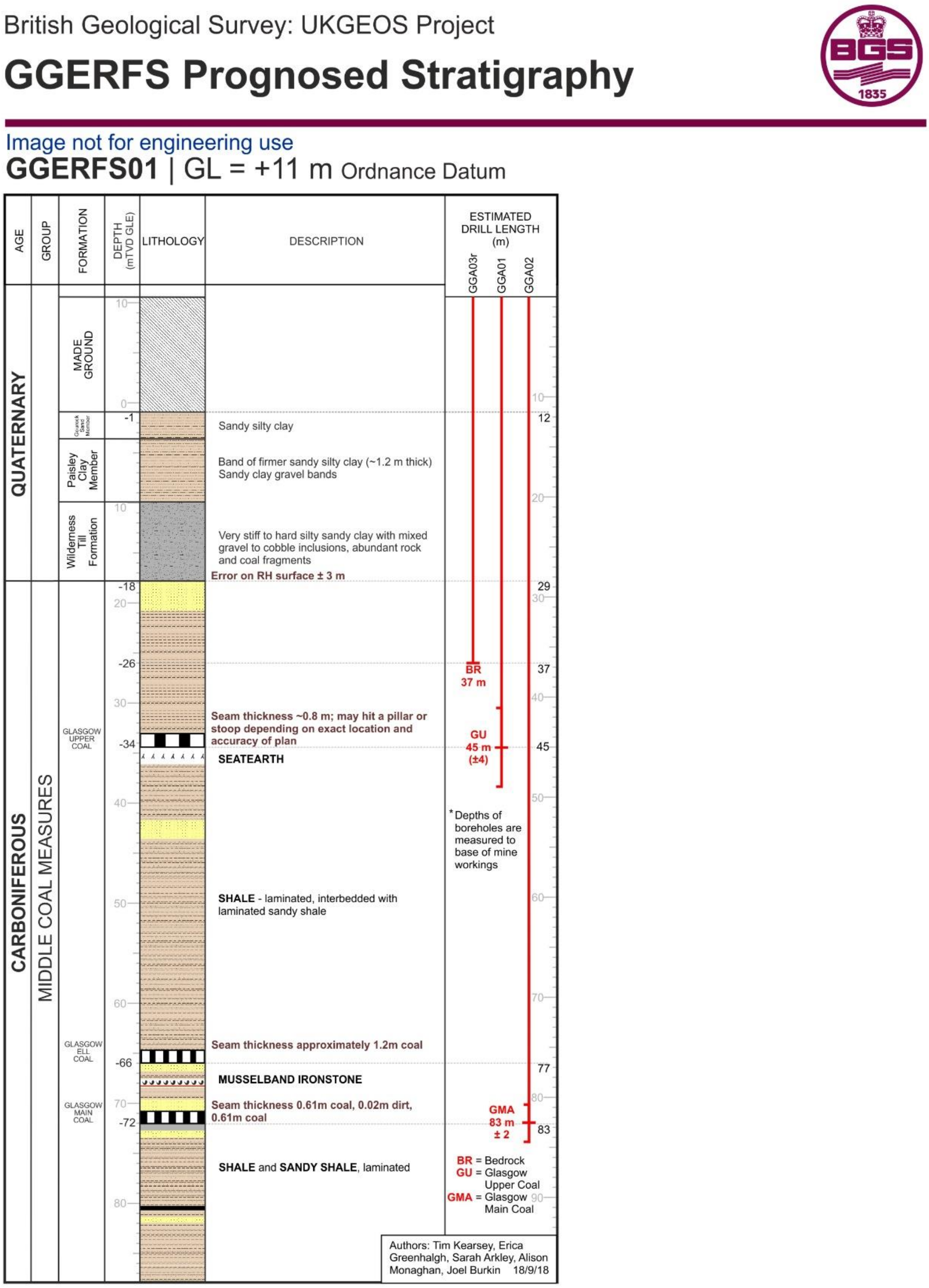


Figure 6 Pre-drill prognosis for site GGERFS01, boreholes GGA01, GGA02, GGA03r based on semi-regional geological models and nearby legacy boreholes.