British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

UK Research and Innovation

UK Geoenergy Observatories: Glasgow Geothermal Energy Research Field Site

- Science infrastructure

BRITISH GEOLOGICAL SURVEY

UKGEOS PROGRAMME

UKGEOS REPORT G0100, BGS OPEN REPORT OR/18/037

UK Geoenergy Observatories: Glasgow Geothermal Energy Research Field Site

SCIENCE INFRASTRUCTURE

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BRITISH GEOLOGICAL SURVEY

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Summary

The purpose of this report is to give an overview of the planned research infrastructure and proposed data acquisition at the Glasgow Geothermal Energy Research Field Site. The report also gives a brief overview of the geological characterisation and environmental baseline at the site.

The report is intended for a technical, science community audience. It summarises the state of play at August 2018, is subject to change and will be updated.

Please note that in the information below, all designs, infrastructure, kit, data to be collected etc. are subject to change.

Foreword

This report presents a record of the infrastructure provided by the UK Geoenergy Observatories Glasgow Geothermal Energy Research Field Site. It sets out the basic monitoring, sample collection and analysis that will be carried out by the British Geological Survey on behalf of the UK research community and international collaborators. All data generated by the British Geological Survey and researchers who use the facility will be freely and openly available. It is expected that individual research projects, funded separately, will have specific operational requirements, and where possible on the grounds of capability and capacity these will be accommodated, following discussion with and approval from the facility's management team.

The design of the infrastructure was based on the requirements of the UK Geoenergy Observatories' Science Plan, which was generated following community consultation. As with all drilling projects, the realities of what can be achieved in the context of geological constraints, health and safety, and budget have meant that the final design is necessarily a compromise. Researchers should use this document as the definitive description of the Observatories' infrastructure, and refer to it in their published outputs.

David Manning

NERC Senior Science User

1 Project overview

1.1 OVERVIEW

The UK Geoenergy Observatories (UKGEOS) project aims to establish new centres for world-leading research into the subsurface environment. The knowledge generated will contribute to the responsible development of new energy and subsurface technologies both in the UK and internationally.

The project follows the Government's 2014 announcement that it would allocate £31 million to create world-class, subsurface energy-research test centres. The BGS is responsible for delivering the research infrastructure and will operate the facilities on behalf of the research community over their 15-year lifetime.

The Science Plan, developed through a consultation process, ensures that UKGEOS provides for the current and future needs of the scientific user community. The research field sites will allow independent, rigorous and replicable observations of subsurface processes and stimulate research on underground energy technologies that will answer vital questions about how they affect the environment.

The BGS worked with the wider geoscience community to identify the Clyde Gateway area in Glasgow and Rutherglen as the preferred site for the Glasgow Geothermal Energy Research Field Site (GGERFS; Figure 1). The focus of the research infrastructure at this site is very low enthalpy mine water geothermal and energy storage in an urban area with a complex prior land use. The area is typical of many towns and cities above abandoned coal mine workings.

The other research field site, described in a separate document (Kingdon et al., 2018), will be in the Thornton area (Cheshire) and will focus on a range of subsurface energy technologies.

Figure 1 View over the Cuningar Loop, looking east towards Glasgow city centre. Borehole locations (numbered) are indicated by green and purple arrows. Photo reproduced with permission of Clyde Gateway URC.

1.2 LOCATION AND SCIENCE POTENTIAL

The Glasgow Geothermal Energy Research Field Site is located in the Clyde Gateway regeneration area of eastern Glasgow (Glasgow City Council) and Rutherglen (South Lanarkshire Council; Figure 2). Chosen for its science potential, this location has many benefits for geoscientists from both research and commercial backgrounds.

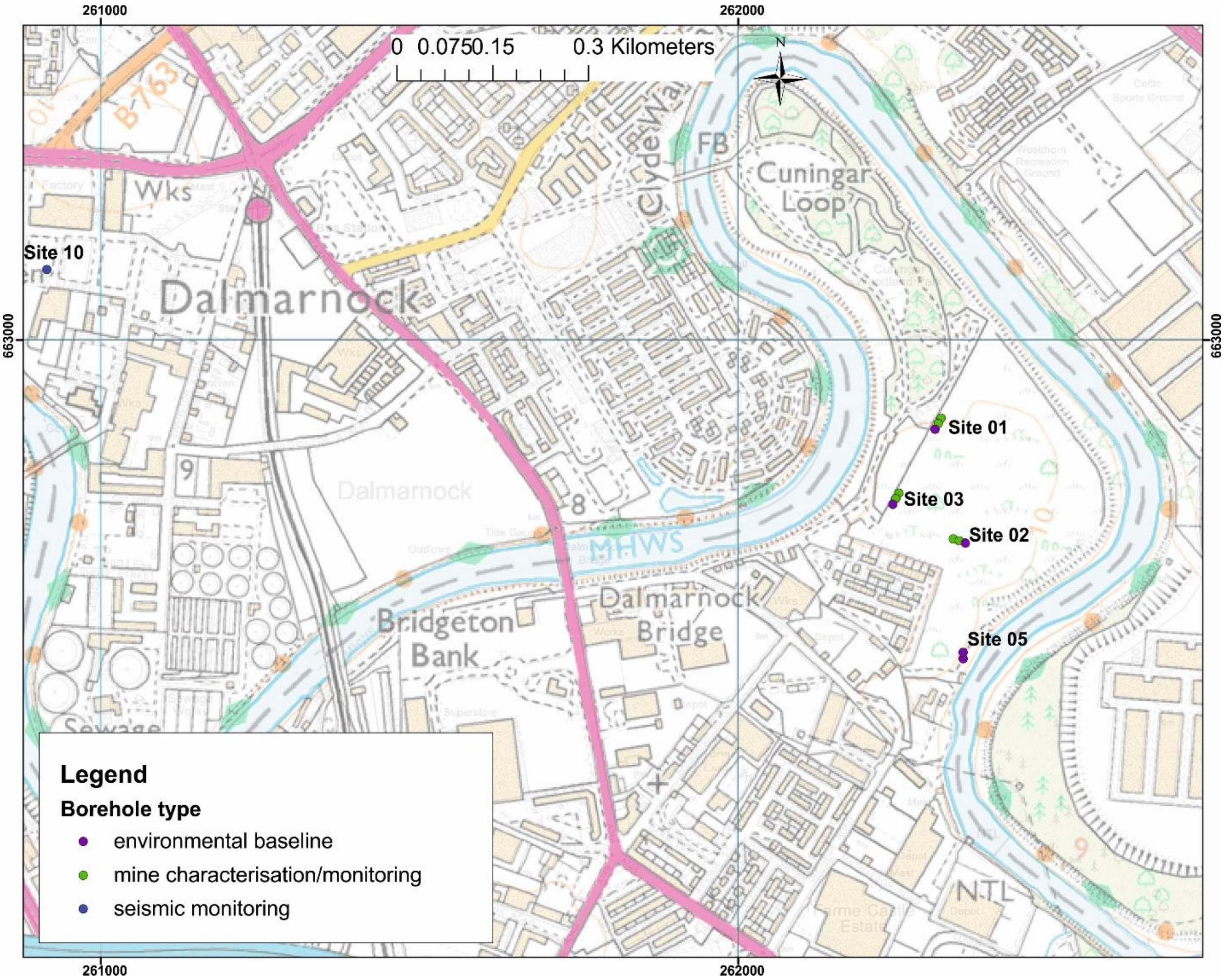

Figure 2 Summary map of proposed borehole locations. Glasgow City Council area is to the north of the River Clyde and South Lanarkshire Council area is to the south. The National Grid and other Ordnance Survey data ©Crown Copyright and database rights 2018. Ordnance Survey Licence No. 100021290 EUL.

Man-made deposits (made or artificial ground) As a result of the areas industrial past**,** there is a widespread made (artificial) ground cover reaching substantial thicknesses in places (> 10 m). A range of compositions are proved from coal mine waste to housing demolition rubble, with science challenges around the feasibility of low-temperature geothermal energy in a post-industrial urban area.

Superficial deposits – Near the surface is a complex sequence of variably permeable Quaternary sediments that are representative of glacial and post-glacial sediments across northern parts of the UK. They provide opportunities for research relating to anthropogenic influences, groundwater flow and transport surface to subsurface.

Mined Coal Measures – The Scottish Coal Measures Group is characterised by coal-bearing fluvio-deltaic sedimentary rocks in cyclical sequences of mudstone, siltstone, seatearth (rootlet-bearing palaeosol), sandstone and coal. Up to seven coal mine workings to depths of a few hundred metres are recorded beneath the area, providing a 'typical' low enthalpy geothermal mine water resource to be characterised.

Structural and basin complexity - The Clyde Gateway area has a typical level of faulted and gently-folded structural complexity for coalfields in Central Scotland (Figure 3, 6). The faulted character is important in providing opportunities to study fault transmissivity and/or sealing in the mined and unmined bedrock.

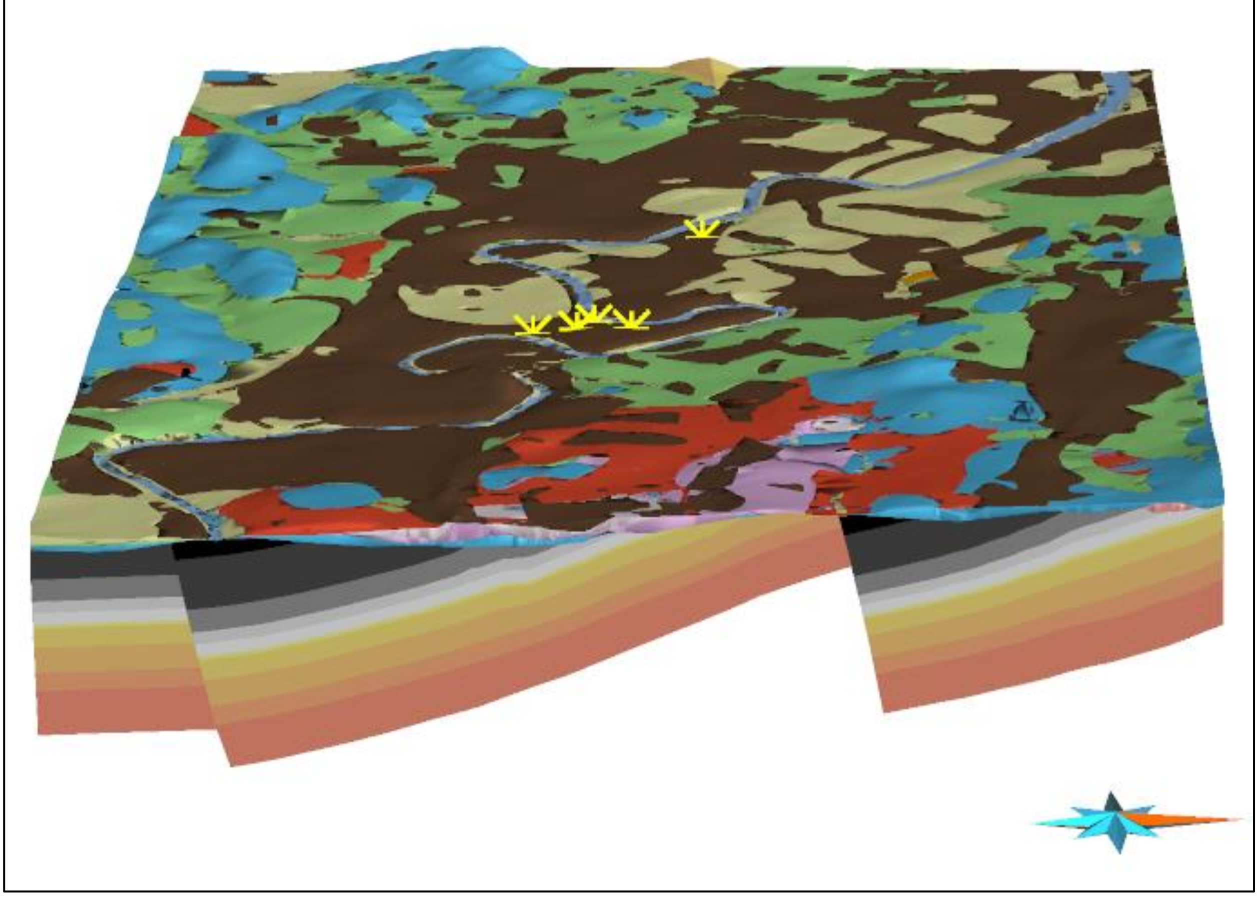

Figure 3 Image of the 7 x 4 km model geological model for the research site, looking west, model to depth of c.300 m. The Scottish Coal Measures Group is represented in the black to orange colours. Superficial and artificial deposits are shown to scale in blue, green, red, pink and brown (see Table 1), with UKGEOS borehole locations shown at the yellow symbols.

Extensive existing data and interpretations – The area is characterised from existing geological data, including abundant borehole datasets (some with hydrogeological and engineering data), mine abandonment plans that include fault information, and an existing set of regional geochemical soil and stream sediment analyses. Legacy 2D seismic data, hydrocarbon well data and bedrock hydrogeology/hydrogeochemistry/temperature data are available from similar Carboniferous sequences across Central Scotland. Existing geological and hydrogeological models at a range of scales form a framework that can be built on over the next 20 years as further data are generated.

1.3 SCOPE OF THE FACILITY

Phase 1 of the Glasgow Geothermal Energy Research Field Site is proposed to cover five sites, four in the Cuningar Loop area (Sites 01, 02, 03, 05; Figures 2, 9) and one in the Dalmarnock area (Site 10; Figures 2, 11). Phase 1 characterisation and monitoring boreholes will establish the baseline, provide data to inform risks and enable a Phase 2 geothermal and science infrastructure to be designed and installed.

The Phase 1 boreholes comprise 6 mine water, 5 environmental baseline and a seismic monitoring borehole of between 9 and 199 m drilled length. These boreholes will be fitted with sensors that will track groundwater levels and temperature, dynamic geoelectrical properties and seismicity within the subsurface. Additional sensors at the ground surface will monitor gas and ground motion, plus there will be sampling and analysis of groundwater, surface water and soil geochemistry. Open access data and information will be provided online allowing wide public observation of Glasgow's subsurface.

The Phase 1 boreholes will yield a limited amount of rock core and cuttings samples. This will be available to the research community for future research after being geologically described, and the core will be scanned with state-of-the-art core scanners to characterise its physical and geochemical properties (Appendix A).

The Glasgow Geothermal Energy Research Field Site will be open to researchers for field experiments from 2020. Researchers will have access to the borehole arrays and the associated instrumentation, as well as having the opportunity to deploy their own equipment. The vision is for researchers internationally to focus their efforts in this area, creating a world-class characterised block of rock, which will allow world-leading science, leading to a step-change in geological and process understanding.

To facilitate research at the field site, the British Geological Survey will provide the onsite compounds and at BGS Keyworth facilities will be provided for core viewing and sampling, core analysis (physical and geochemical) and core scanning. A state of the art UKGEOS online portal will stream data from the site and also provide a repository for all data and science understanding generated at the site.

2 Geology

2.1 SITE LOCATION

The Glasgow Geothermal Energy Research Field Site is located on the western side of the Central Coalfield of the Midland Valley of Scotland. It is located within glacial and post-glacial Quaternary superficial deposits, overlain by a variable thickness of artificial (made) ground. These deposits rest on approximately 300 m of Scottish Coal Measures Group bedrock. Underlying this are older Carboniferous strata of the hundreds of metres thick Clackmannan and Strathclyde groups. The prior industrial land use has left a legacy of abandoned, flooded mine workings and a variety of artificial ground forming the current land surface.

2.2 QUATERNARY GEOLOGY

A complex succession of Quaternary superficial deposits covers the research area, including widespread glacial till and marine, lacustrine and fluvio-glacial deposits, overlain by fluvial deposits, recent alluvium and anthropogenic (man-made) deposits.

The Quaternary deposits are of variable thickness, up to 30 m. The upper surface of bedrock was incised, with thicker accumulations of superficial deposits infilling a broadly NW–SE trending channel following the modern day River Clyde. There is widespread made, filled and landscaped ground relating to a variety of prior industrial land use, in some places this is 10–15 m thick. Table 1 summarises the sequence.

Code	Equivalent description on 1: 10, 000 scale published map
Water	Unattributed polygons
Made Ground	Made Ground, Made Ground and Worked Ground, Infilled Ground
Peat	Peat – blanket or basin peat, Flandrian
Law Sand and Gravel Member	Alluvium – modern river floodplains – located along the upper reaches and tributaries to the River Clyde, Flandrian. Also includes some Alluvial Fan Deposits, Flandrian and some River Terrace Deposits, Flandrian.
Gourock Sand Member	Marine Deposits – located along the lower reaches of the River Clyde, Flandrian and Alluvium – modern river floodplains – along the upper reaches of the River Clyde, Flandrian
Killearn Sand and Gravel Member	Generally Raised Marine Deposits, Devensian, Raised Marine Deltaic Deposits, Devensian or Raised Marine Intertidal and Subtidal Deposits, Devensian
Paisley Clay Member	Generally Raised Marine Deposits, Devensian or Raised Marine Intertidal and Subtidal Deposits, Devensian
Bridgeton Sand Member	Largely concealed beneath younger deposits, where present, exposures usually represented as Raised Marine Deposits, Devensian
Ross Sand Member	Glaciolacustrine Deposits, Devensian Glaciolacustrine Deltaic Deposits, Devensian or Glaciofluvial Deposits, Devensian
Ross Sand Member (silt, sand)	Largely concealed beneath younger deposits, identified at depth from borehole data, rare exposures represented as Glaciolacustrine Deposits, Devensian or Glaciolacustrine Deltaic Deposits, Devensian
Broomhouse Sand and Gravel Formation (sand and gravel)	Largely concealed beneath younger deposits, where present, exposures usually represented as Glaciofluvial Deposits, Devensian, but also as Glaciofluvial Ice-Contact Deposits, Devensian
Broomhouse Sand and Gravel Formation (sand)	Not recorded on the maps in the Clyde Gateway area (concealed beneath younger deposits), identified at depth from borehole data
Wilderness Till Formation	Till - Devensian
Cadder Sand and Gravel Formation	Generally concealed beneath younger deposits, identified at depth from borehole data, rare exposures represented as Glaciofluvial Deposits, Devensian

Table 1 Summary of superficial deposits and artificial ground sequence in the Clyde Gateway area

The precise relationships between the Quaternary deposits are complex, varying laterally and vertically across short distances (Figure 4), making extrapolation difficult in areas where borehole data are sparse or absent. For that reason, both interpretative and stochastic modelling has been undertaken.

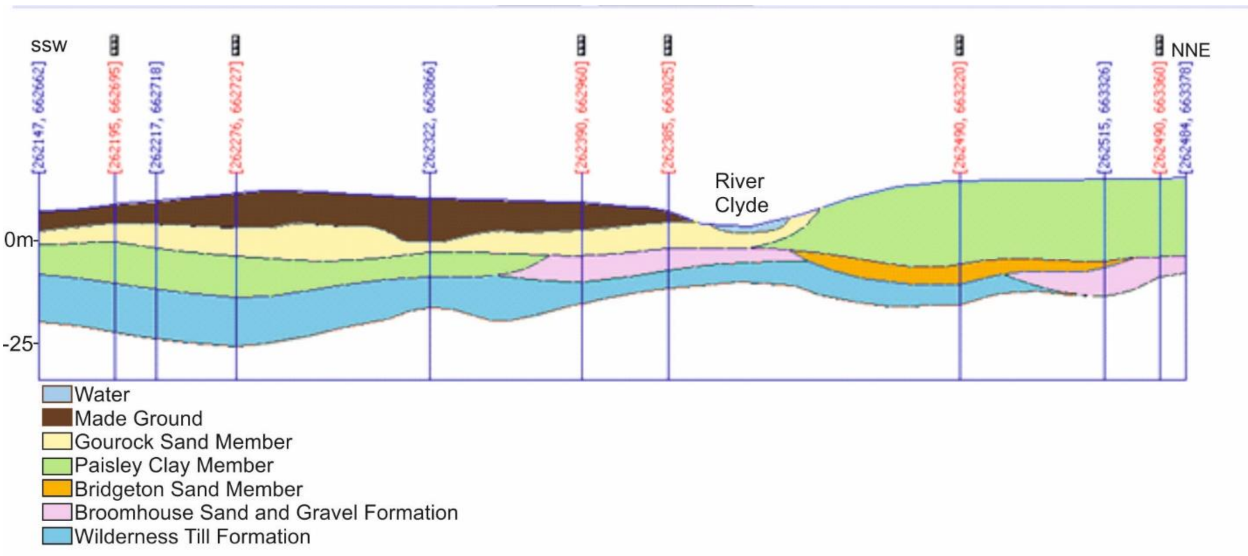

Figure 4 Example SSW–NNE cross-section of superficial deposits in the vicinity of the research site. Vertical exaggeration x 3. Borehole constraint points shown in red. Ground surface derived from NEXTMap Britain elevation data from Intermap Technologies.

Further information is available from Kearsey et al. (2015), Monaghan et al. (2013), Monaghan et al. (2017).

2.3 BEDROCK GEOLOGY

Geological maps and borehole data are available to view on the BGS GeoIndex Onshore. Data from mine abandonment plans includes extent, depth, working type, faults etc for the stack of seven worked coal seams. The mine workings date from 1810–1934 with total extraction and stoop and room workings shown. It is expected that total extraction areas collapsed within a few years of mining to form a waste, and that the mines will be flooded.

Bedrock strata that will be accessed by the facility are the Scottish Upper, Middle and Lower Coal Measures formations of the Westphalian Scottish Coal Measures Group (e.g. Table 2; Figure 5). These lithologically variable sedimentary rocks are well documented by borehole records and correlated using coal seams and marine bands.

Analysis of borehole, mine abandonment plan, map and legacy 2D seismic data to the north-east of the Clyde Gateway shows gently folded synclinal structures dissected by faults on a range of orientations (Figure 6). To the southeast of the study area the NW–SE trending Dechmont Fault is a major basin-bounding structure. E–W trending structures such as the Rutherglen, Shettleston and Great Dyke faults dissect the succession with smaller NNE to N trending structures.

Approximate depth relative to OD, metres, Location 01	**Stratigraphy**
-34	Glasgow Upper Coal (workings)
-66	Glasgow Ell Coal (workings)
-73	Glasgow Main Coal (workings)
-91	Humph Coal (workings)
-100	Glasgow Splint Coal (workings)
-104	Virgin Coal
-123	Airdrie Blackband Coal
-161	Airdrie Virtuewell
-167	Kiltongue Coal (workings)
-177	Base Coal Measures Group

Table 2 Estimated depths to mined coals and stratigraphic boundaries at one of the proposed borehole locations (GGERFS01)

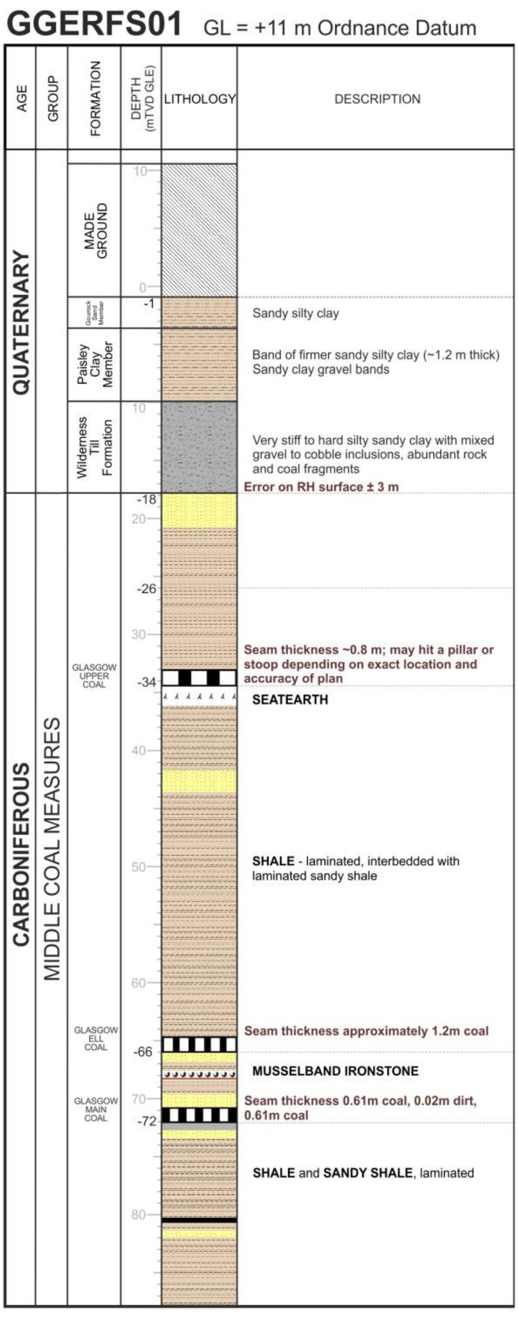

Figure 5 Borehole prognosis for site 01 based on surrounding borehole records, mine abandonment plans and BGS 3D modelling. Yellow indicates sandstone, black and white fill indicates mined coal seams.

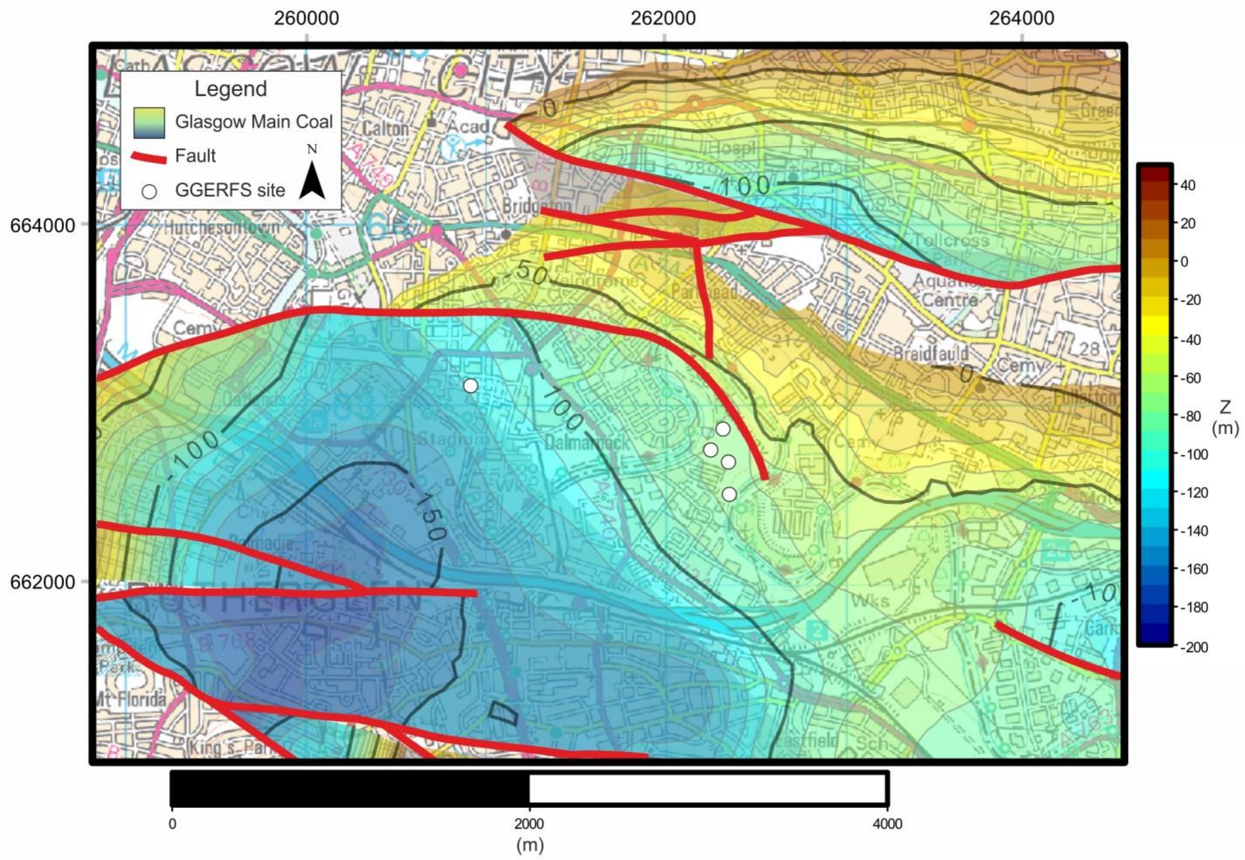

Figure 6 Depth grid to the Glasgow Main Coal (metres relative to Ordnance Datum) from the bedrock model described in Kearsey & Burkin (2018). Ordnance Survey data ©Crown Copyright and database rights 2018. Ordnance Survey Licence No. 100021290 EUL.

Further information available from: BGS (2007), Monaghan et al. (2013), Monaghan et al. (2017), Kearsey and Burkin (2018).

2.4 GEOLOGICAL MODELS

BGS has updated 3-dimensional geological framework models of the superficial and bedrock geology (see Figures 3, 6 above), integrating a wide range of available data and knowledge. These models are currently progressing through a quality control system and will be released in due course. They will be continually updated as new data emerges during borehole drilling. Stochastic models of the superficial deposits also exist (e.g. Kearsey et al., 2015). The geological framework models form the basis for mine, hydrogeological and thermal models.

3 Hydrogeology

3.1 OVERVIEW

Existing available hydrogeological, hydrogeochemical and groundwater temperature data have been collated for the research area before borehole drilling starts. In Glasgow, neither surface water nor groundwater are used as a drinking water resource

3.2 HYDROGEOLOGY OF THE SUPERFICIAL DEPOSITS

Much more is known about the hydrogeology of superficial deposits than about bedrock in Glasgow and the Clyde Gateway area. The Quaternary geological sequence in the central

Clyde valley in Glasgow, including the Clyde Gateway area, forms a shallow complex aquifer system with a sequence of hydrogeologically heterogeneous lithostratigraphic units. Three Quaternary lithostratigraphic units – the Bridgeton Sand, Gourock Sand and Paisley Clay members – together form a linear aquifer approximately 2 to 3 km wide and typically between 10 and 30 m thick beneath central Glasgow. This aquifer is highly heterogeneous both naturally, due to varying lithology within aquifer units and to the varying influence of the tidal River Clyde with distance from the river; and due to urban influences, such as altered surface permeability, subsurface flowpaths, and urban recharge (Ó Dochartaigh et al., in press).

The national map of groundwater vulnerability indicates that groundwater in the uppermost Quaternary aquifer is highly vulnerable across much of the area, with zones of low vulnerability. However, this national-scale map is not likely to provide an accurate assessment of the actual vulnerability of groundwater in the small urban Clyde Gateway area. The widespread presence of anthropogenically altered ground – not accounted for in the national scale map - is likely to have a major impact on local groundwater vulnerability and this has been considered in environmental assessments for the research site (Ramboll, 2018 a,b,c,d)

3.3 HYDROGEOLOGY OF THE BEDROCK

Unmined Carboniferous sedimentary rocks in the Central Belt of Scotland typically form multi-layered and vertically segmented aquifers. The typically fine-grained, well-cemented rocks have low intergranular porosity and permeability, and groundwater flow and storage dominantly occur in fractures in the rock. Hydraulic aquifer properties therefore depend largely on the local nature of fracturing in the rock (Ó Dochartaigh et al., 2015). Overall, the unmined rocks tend to form moderately productive aquifers – aquifer properties values are given in Table 3. Sandstone units within the sedimentary sequence generally have the highest transmissivity and storage capacity, and therefore tend to act as discrete aquifer units, interspersed by lower permeability siltstones, mudstones and (undisturbed) coal seams (Ó Dochartaigh et al., 2015).

Groundwater can be present in the aquifer under unconfined or confined conditions, which can vary between different sandstone and other sedimentary units and at different depths. Groundwater heads therefore vary between different aquifer layers (Ó Dochartaigh et al. 2015).

Groundwater flow paths through the aquifer are thought to be complex, due to their naturally layered nature and the predominance of fracture flow, and potentially to the influence of faults. This may tend to promote preferential sub-horizontal flow, such as within sandstone units, and sub-vertical flow, such as via transmissive fault zones. Flow paths are likely to be relatively deep (100s of metres) and long (1–10 km). Previous assessments suggested that Glasgow acts as the focal point for much of the groundwater discharge from Carboniferous aquifers from the Central Coalfield area, with prevailing groundwater flow paths from the east, north-east and south-east (Hall et al., 1998), but there is little measured hydrogeological data to support this hypothesis.

	Porosity (%)	Matrix hydraulic conductivity (m/d)	Transmissivity (m^2/d)	Specific capacity (m3/d/m)	Operational yield (m^3/d)
Carboniferous aquifers – not extensively mined for coal	12–17 (34)	0.0003–0.1 (37)	10–1000 * (5)	48–132 * (46) (minimum 0.43; maximum 1320) *	131–418 (348)

	Porosity (%)	Matrix hydraulic conductivity (m/d)	Transmissivity (m^2/d)	Specific capacity ($m^3/d/m$)	Operational yield (m^3/d)
Carboniferous aquifers – extensively mined for coal			10–1000 * (5)	48–132 * (46) (minimum 0.43; maximum 1320) *	1987–3279 (171) (minimum 41; maximum 22 248)

* May refer to both mined and nonmined aquifers
Ranges of values refer to mean and median values except where indicated
Number of values indicated in brackets
Data from the British Geological Survey

Table 3 Summary of available aquifer properties data for Carboniferous sedimentary aquifers of Scotland: (top) not extensively mined for coal; (bottom) extensively mined for coal. From Ó Dochartaigh et al. (2015).

3.3.1 Impacts of mining

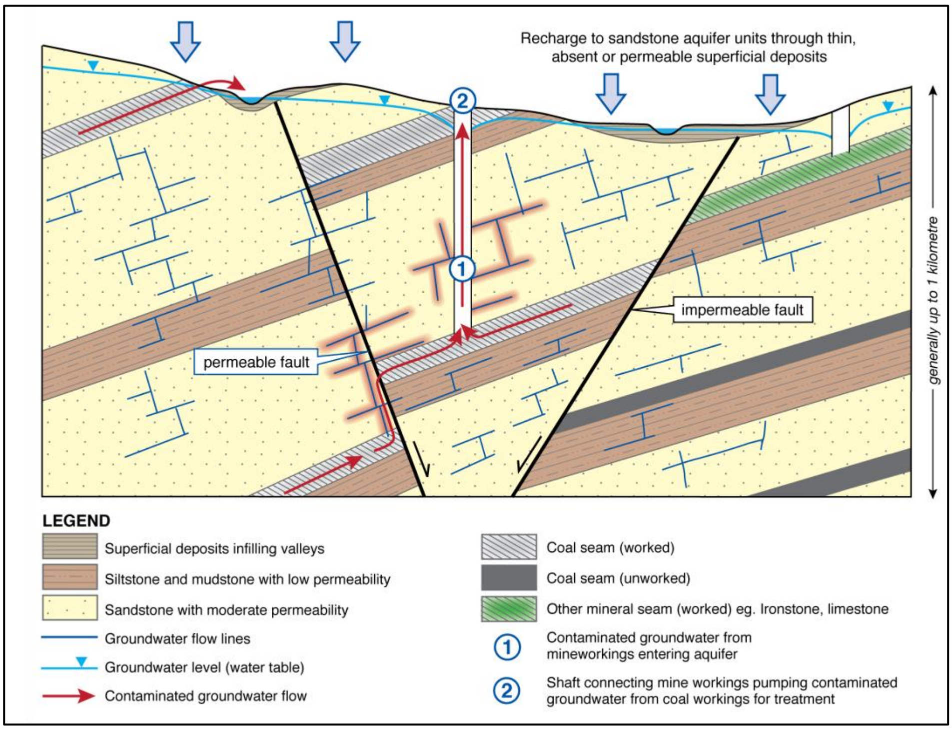

Figure 7 Mined hydrogeology conceptual model for central Scotland from Ó Dochartaigh et al. (2015).

Mining in Carboniferous sedimentary rocks has significantly changed natural hydrogeological conditions. Groundwater flow paths are likely to be even more complex in mined aquifers than in undisturbed Carboniferous aquifers

Mine voids (shafts and tunnels) can artificially and greatly increase aquifer transmissivity and can link formerly separate groundwater flow systems both laterally and vertically (Figure 7). Aquifer storage can also be locally increased. Even where mine voids have subsequently collapsed, deformation of the surrounding rock mass is likely to cause further changes in transmissivity and, to a lesser degree, storage (Younger and Robins, 2002).

Quantitative aquifer properties data from borehole test pumping are relatively rare for formerly mined aquifer zones in Carboniferous rocks in Scotland. However, records of specific capacity from boreholes drilled in aquifers which have been extensively mined, many of which intercept mine workings, give an indication of the range in aquifer properties and how this varies from the unmined aquifers; and there are many records of yields, and fewer specific capacity values, from mine dewatering boreholes (Table 3), which are typically higher than for the same aquifers that have not experienced extensive coal mining.

3.3.2 Temperature

Though there are no direct borehole temperature measurements within the Clyde Gateway area, there are 13 measurements from within 20 km (Figure 8). This existing dataset indicates that mine water temperature in the planned boreholes is likely to be around 12 °C.

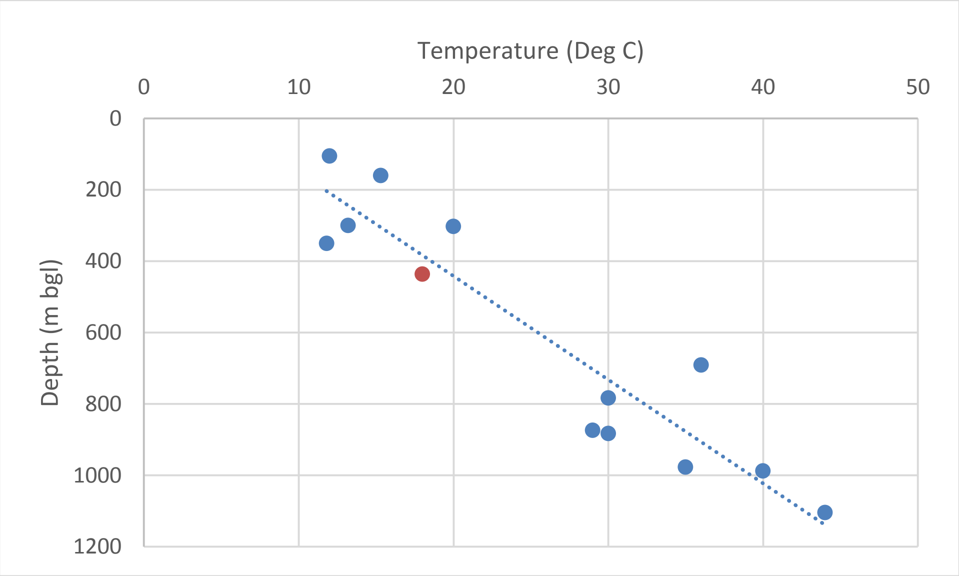

Figure 8 Measured temperature and depth within 20 km of the Clyde Gateway area; 10 data points from Burley et al. (1984), Rollin et al. (1987), and DECC Onshore Well archive. The red data point is temperature measured in the Highhouse Colliery. The geothermal gradient is 30.2 °C/km with a surface temperature of 7.3 °C, reproduced from section 5.2 of Monaghan et al. (2017).

3.4 HYDROCHEMISTRY

Data on the hydrogeochemistry within superficial and artificial ground is contained within site investigation reports and summarised in reports for the planning application (Ramboll, 2018 a,b,c,d). Results are highly variable dependent on location, but some sites close to the planned borehole locations show exceedances to resource protection values in both the shallow (superficial deposits) groundwater and deeper (near top bedrock) groundwater.

There is little recent information on groundwater chemistry in the Carboniferous sedimentary aquifer in Glasgow. Some regional bedrock hydrochemistry information is available from Baseline Scotland dataset (Ó Dochartaigh et al., 2011). The natural chemistry of groundwater in Carboniferous sedimentary aquifers is often moderately to highly mineralised (values in Ó Dochartaigh et al., 2011).

Groundwater quality can be significantly affected by mining. Groundwater discharges from mine workings are often strongly mineralised, with high specific electrical conductivity (SEC) and particularly high concentrations of HCO_3, Ca, SO_4, Fe and Mn, and low in dissolved oxygen. The pH values are generally well buffered and alkalinity is high, indicating significant reaction with carbonate material in the aquifers (Ó Dochartaigh et al., 2011). Acid mine water discharge is not currently a known problem in Glasgow, and past investigations at a number of sites have indicated good quality groundwater in abandoned mine workings (Glasgow City Council, pers. comm.).

More hydrogeology information is available in from Ó Dochartaigh, et al. (2011), Ó Dochartaigh, et al (2015).

More hydrogeological modelling information from: Bianchi et al. (2015), Turner et al. (2015).

3.5 ADDITIONAL CHARACTERISATION AND MONITORING DATA SOURCES

Summaries of surface water, soil chemistry, baseline seismicity and engineering geology datasets are given in Monaghan et al. (2017) with other summaries of baseline datasets:

Surface water: Fordyce et al, (2004), Smedley et al. (2017)

Soil chemistry: Fordyce et al. (2012), Kim et al. (In press)

Ground motion: Bateson et al. (2018)

Stress and seismicity of central Scotland: Baptie et al. (2016)

Geological models: Kearsey et al. (In press), Williams et al. (In press)

Mine geothermal in Glasgow: Banks et al. (2009).

4 Research infrastructure

4.1 OVERVIEW OF SCIENCE INFRASTRUCTURE

This text describes borehole arrays re-scoped to fit within budget (note the planning applications cover a greater number of boreholes)

Phase 1 of the Glasgow Geothermal Energy Research Field Site research infrastructure will comprise of three borehole arrays:

- Array A Mine water characterisation and monitoring
- Array B Environmental baseline characterisation and monitoring
- Array C Seismic monitoring

The infrastructure also includes the following science installations and environmental baseline monitoring datasets:

- Groundwater
- Surface water
- Ground motion
- Soil or ground gas
- Soil chemistry

The Phase 2 geothermal and science infrastructure will be finalised once the results of the Phase 1 characterisation and monitoring boreholes are available. Sections 4.2 to 4.5 provide an overview of the infrastructure, instrumentation and data available for research.

4.2 ARRAY A MINE WATER CHARACTERISATION AND MONITORING

4.2.1 **Overview**

Array A boreholes will measure data from what we believe to be a representative set of mine workings to characterise the mined rock volume and mine water hydrogeology. The boreholes will target two levels of mine workings at drilled depths from around 45 m to 90 m and will likely penetrate different types of abandoned mine workings. Data from the mine water borehole array will inform the design and scope of the Phase 2 geothermal research infrastructure

The array will allow scientists to study in great detail spatial and temporal connections and variability within a mined rock volume. The aim of the array is to:

- Improve the scientific understanding of the subsurface mine water environment (i.e. subsurface flow, heat and fluid connectivity, sustainability of mine water resources, fluid-rock mass interactions) through the collection and interpretation of measured data such as mine water temperature, geochemistry, levels, flow and storativity etc.
- To characterise initial conditions and provide ongoing baseline monitoring of the mine water hydrogeology, against which any future research results can be compared
- To provide continuous downhole data and cross-borehole imaging of geoelectrical and temperature properties of the subsurface in order to monitor natural and induced properties and changes
- Provide open data in easily accessible formats
- Provide borehole infrastructure to test and optimise new technologies, sensors, performance, and operational strategies. Work to study key uncertainties such as dosing, dissolved gas management and clogging could be undertaken in this borehole array.

4.2.2 **Locations**

The mine water characterisation and monitoring boreholes comprise three clusters of two boreholes in the Cuningar Loop (Figure 9). The locations have been chosen to penetrate two levels of mine workings in a triangular arrangement, to characterise the mine water flow at a scale suitable for the heterogeneous geology. Small mapped faults and a coal washout, all within the same larger fault block, are typical of the geology. Different styles of mine working are likely to be encountered – stoop and room and total extraction (stoop and room followed by subsequent total extraction) beneath a sandstone or siltstone/mudstone roof both possibly partially or completely collapsed.

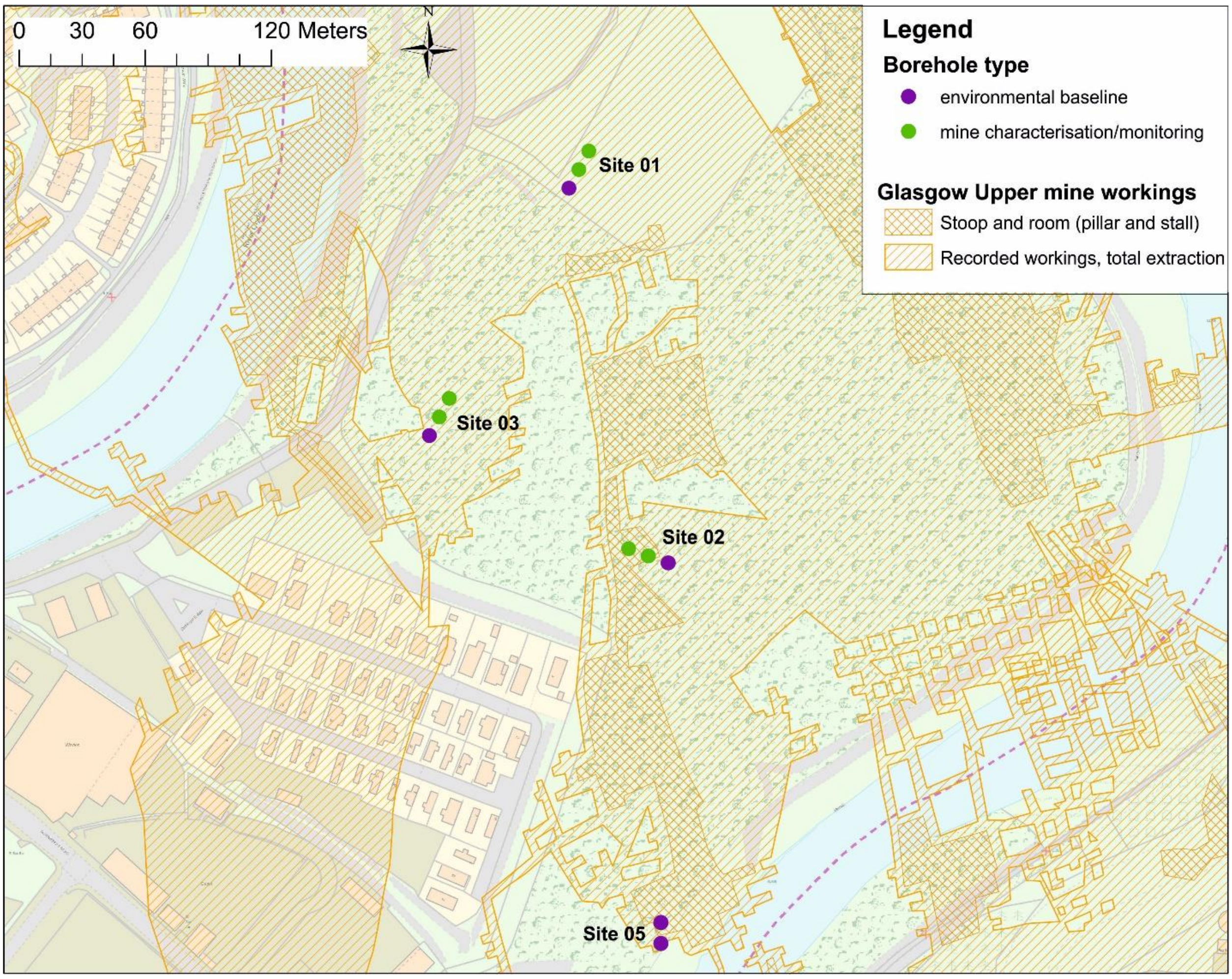

Figure 9 Array A: Mine water characterisation and monitoring (GGERFS01, 02, 03) borehole locations along with the recorded extent of Glasgow Upper mine workings from BGS interpretation of mine abandonment plan records (location error of the order of ± 5 m). Ordnance Survey data ©Crown Copyright and database rights 2018. Ordnance Survey Licence No. 100021290 EUL

4.2.3 **Infrastructure**

At each of the three locations there are two boreholes, each cased and screened within a worked coal seam. Each borehole has an internal casing diameter of 255 mm and will have a 4 mm slot screen of length between 3–10 m (dependent on the condition of the working and fractures above/below; Figure 10). The shallower borehole will target the Glasgow Upper Coal workings at approximately -40 m relative to OD (*c.*50 m drilled depth) and the deeper borehole will target the Glasgow Main Coal workings at approximately -80 m (*c.*90 m drilled depth).

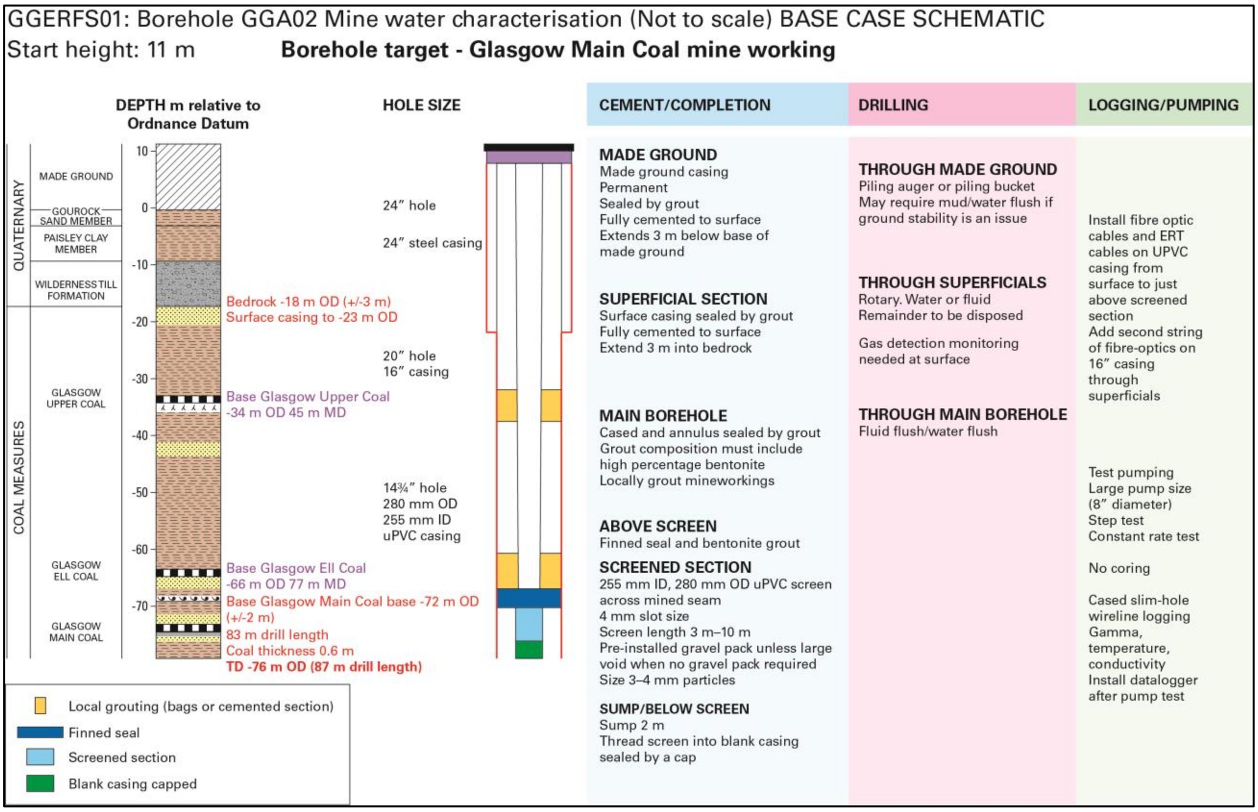

Figure 10 Example of Array A mine water borehole design

The boreholes have been designed to minimise mixing of mined groundwater from different levels and will allow testing of aquifer properties, temperature-pressure monitoring and groundwater sampling of the particular mined seam. This will provide information to understand connectivity, flow and heterogeneity of the mine water system.

The boreholes have been designed with a relatively large diameter, so that they are suitable to be re-purposed as future geothermal abstraction, reinjection and science boreholes. They are suitable for the deployment of pumps and other groundwater equipment.

Electrical resistivity tomography and distributed temperature sensing fibre optic cables are planned to be installed in the bedrock sections of the mine water characterisation and monitoring boreholes.

4.2.4 Scientific instrumentation

The mine water characterisation and monitoring boreholes have been designed to allow for the installation of scientific instrumentation including and for groundwater sampling, for example:

- Pressure-–temperature transducers
- Multi-parameter water quality probes
- Submersible sampling and high-flow pumps

4.2.5 Scientific data acquisition

UKGEOS will deliver the following data from the mine water boreholes:

- Hydraulic head and groundwater temperature and specific electrical conductivity (SEC) – measured via continuously recording, monthly-downloaded pressure-temperature-conductivity transducers, supported by monthly manual groundwater level and conductivity measurements.
- Aquifer properties – pump tests
- Groundwater sampling – repeated groundwater sampling campaigns will collect and analyse groundwater samples from the boreholes. Sampling will take place monthly for at least 1 year to establish a baseline. Appendix B, Table 4 summarises the parameters proposed to be analysed. In addition it is planned to collect samples for geomicrobiology studies, and some additional groundwater samples may be taken to be available for the research community.
- Geophysical logging (cased hole, limited tools (gamma, caliper, probably temperature, conductivity), deepest borehole at each site only)
- Output from electrical resistivity tomography (ERT) and direct temperature sensing (DTS) fibre optic cables
- Cuttings samples collected during borehole drilling, drilling records and logs

All data collected at the site will be made available to researchers.

4.3 ARRAY B ENVIRONMENTAL BASELINE CHARACTERISATION AND MONITORING

Array B provides baseline groundwater data allowing researchers to study the groundwater regime. The array and its associated monitoring will allow scientists to study spatial and temporal variability of groundwater within superficial deposits and near the top of the bedrock. The aim of the array is to:

- Improve the scientific understanding of the subsurface and near surface groundwater environment in particular the subsurface to surface interactions and potential risks associated with mine water geothermal research activities by collecting data relating to water geochemistry, temperature, and level
- To characterise initial conditions and provide ongoing baseline monitoring of the non-mined subsurface hydrogeology, against which any future research results can be compared to identify any environmental change(s) resulting from research activities
- Meet regulatory requirements for developing any future geothermal activities at the site and provide public assurance
- Provide open groundwater monitoring data in easily accessible formats

4.3.1 Locations

Following a rescoping exercise to reduce costs, the environmental baseline borehole array comprises five boreholes in the Cuningar Loop area (Figure 11). Three boreholes target intervals within the superficial deposits and two target unmined zones near the top of the bedrock. This distribution of boreholes is designed to monitor groundwater interactions at the mine water borehole sites and to the south of those sites, in the approximate direction of the predicted groundwater flow.

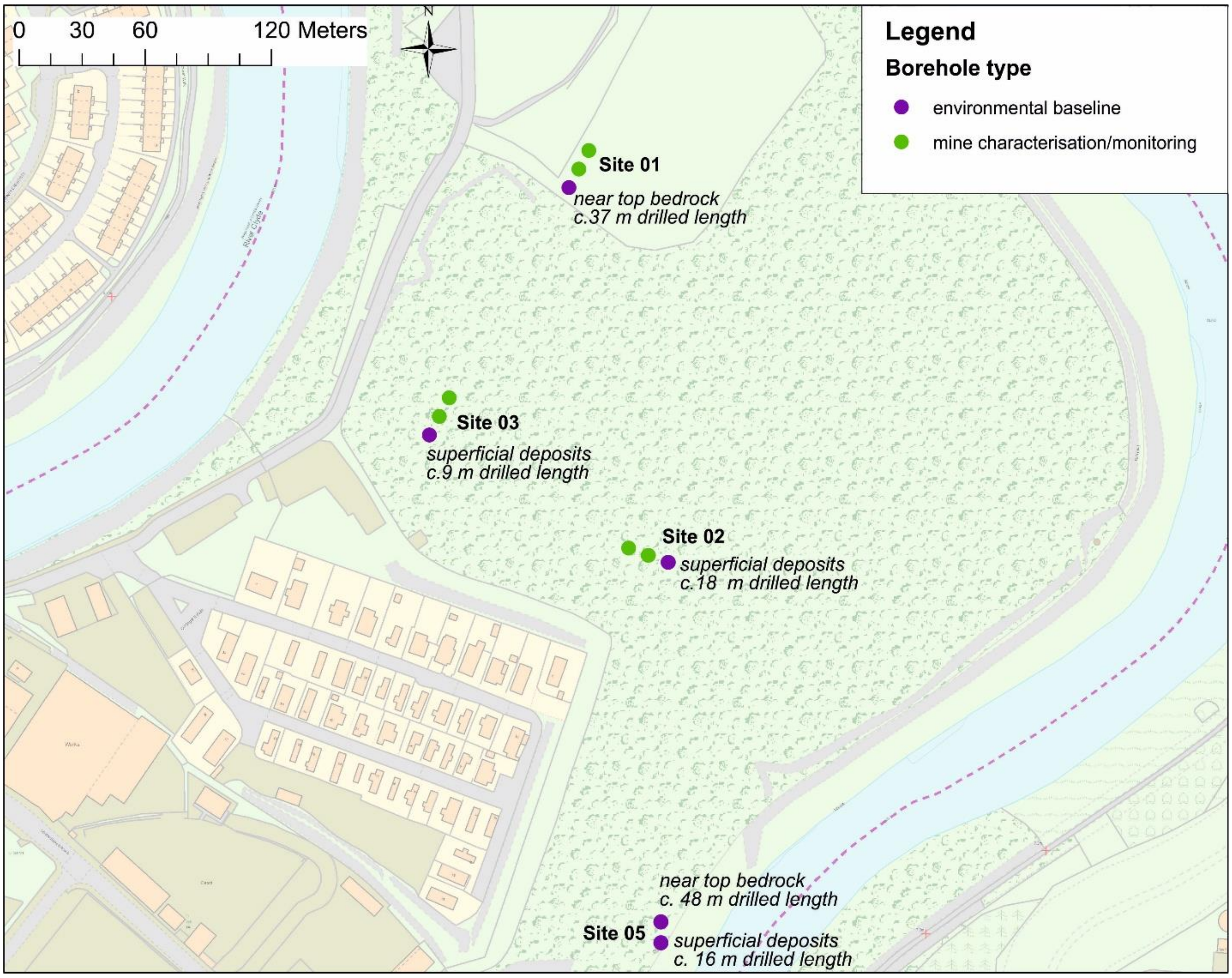

Figure 11 Array B Environmental baseline characterisation and monitoring borehole locations. Ordnance Survey data ©Crown Copyright and database rights 2018. Ordnance Survey Licence No. 100021290 EUL.

4.3.2 Infrastructure

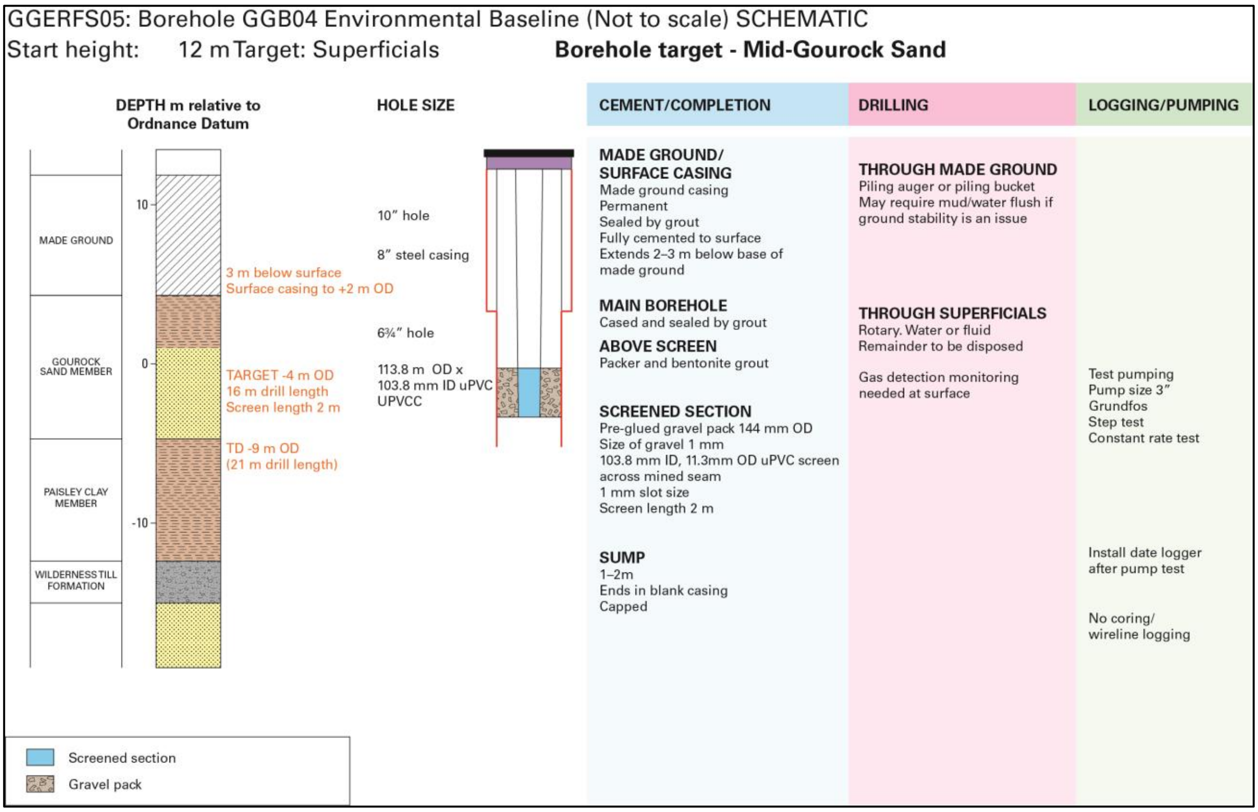

Figure 12 Example of Array B environmental baseline monitoring borehole design for a target in the superficial deposits

Each environmental baseline borehole is cased and screened at its base in the target interval (Figures 12, 13). The superficial deposits boreholes vary in length from 9 m up to 18 m drill length with a 103.8 mm internal diameter casing and a 2 m screened interval across the target depth. The near top bedrock boreholes are range between 37 m and 48 m drill length with a 150 mm internal diameter casing and a 3–10 m screened interval across the zone of interest.

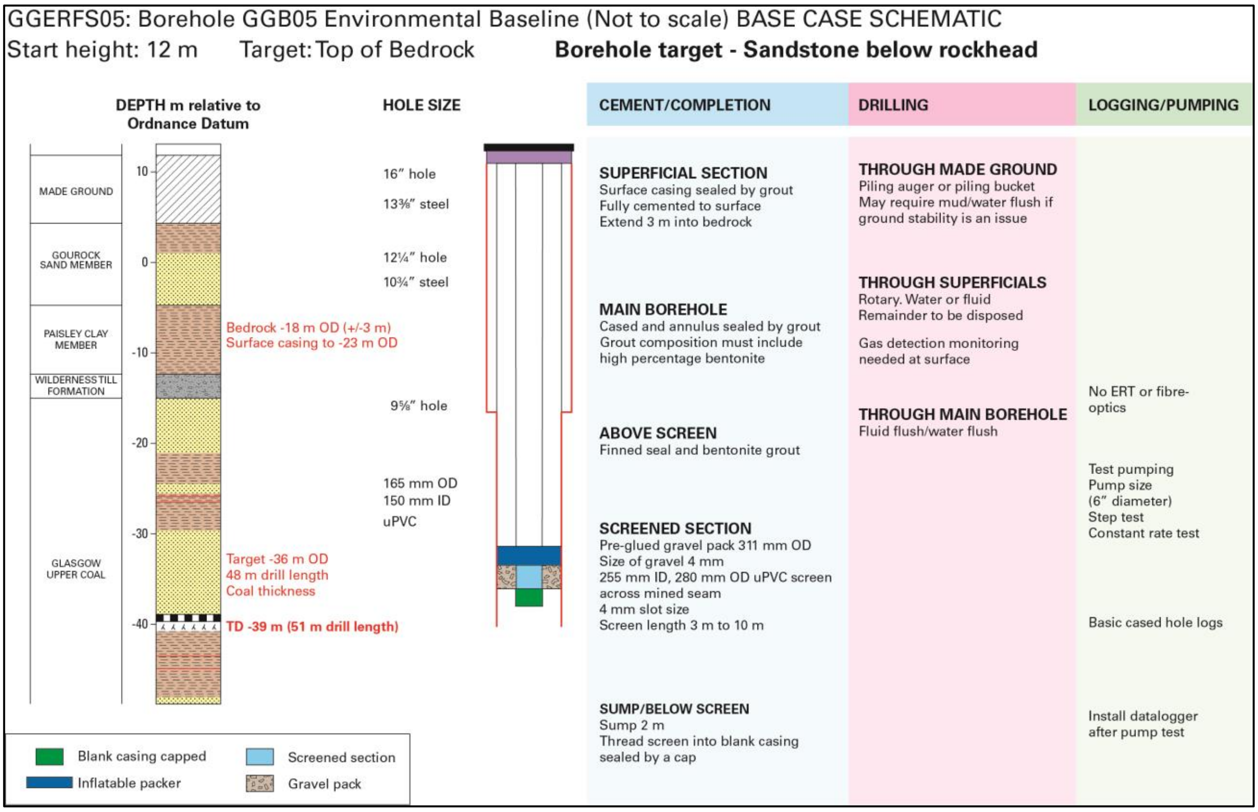

Figure 13 Example of Array B environmental baseline monitoring borehole design for a target near the top of the bedrock

The boreholes have been designed to allow groundwater samples, levels and temperatures to be obtained providing the opportunity to better understand vertical variability in groundwater temperature, chemistry, groundwater head and interactions between bedrock and superficial deposits to be studied.

4.3.3 Scientific instrumentation

All environmental baseline boreholes have been designed to allow for the installation of scientific instrumentation including, for example:

- Pressure-temperature transducers
- Submersible pumps

4.3.4 Scientific data acquisition

UKGEOS will deliver the following data from the environmental baseline boreholes:

- Hydraulic head, groundwater temperature and specific electrical conductivity (SEC) – measured via continuously recording, monthly-downloaded pressure-temperature-conductivity transducers, supported by monthly manual groundwater level and conductivity depth measurements.
- Aquifer properties – pump tests

- Groundwater sampling – repeated groundwater sampling campaigns will collect and analyse groundwater samples from the boreholes. Sampling will take place monthly for at least 1 year to establish a baseline. Appendix B, Table 4 summarises the parameters proposed to be analysed. In addition it is planned to collect samples for geomicrobiology studies, and some additional groundwater samples may be taken to be available for the research community.
- Cuttings samples collected during borehole drilling, drilling records and logs

All data collected at the site will be made available to researchers.

4.4 ARRAY C SEISMIC MONITORING AND CORED BOREHOLE

4.4.1 **Overview**

The GGERFS seismic monitoring borehole is designed to strengthen the national seismic monitoring network in the urban area, so that any felt earthquake can be detected and located. Reliable characterisation of baseline levels of natural seismicity in the vicinity of GGERFS will allow discrimination of any future events that could erroneously be attributed to geothermal activities at the research site. Without this, in the unlikely event that there are any changes in the spatial or temporal behaviour of small seismic magnitude events, these would be obscured by uncertainties.

This is also the cored borehole for GGERFS Phase 1 that is intended to be open-hole wireline logged.

4.4.2 Location

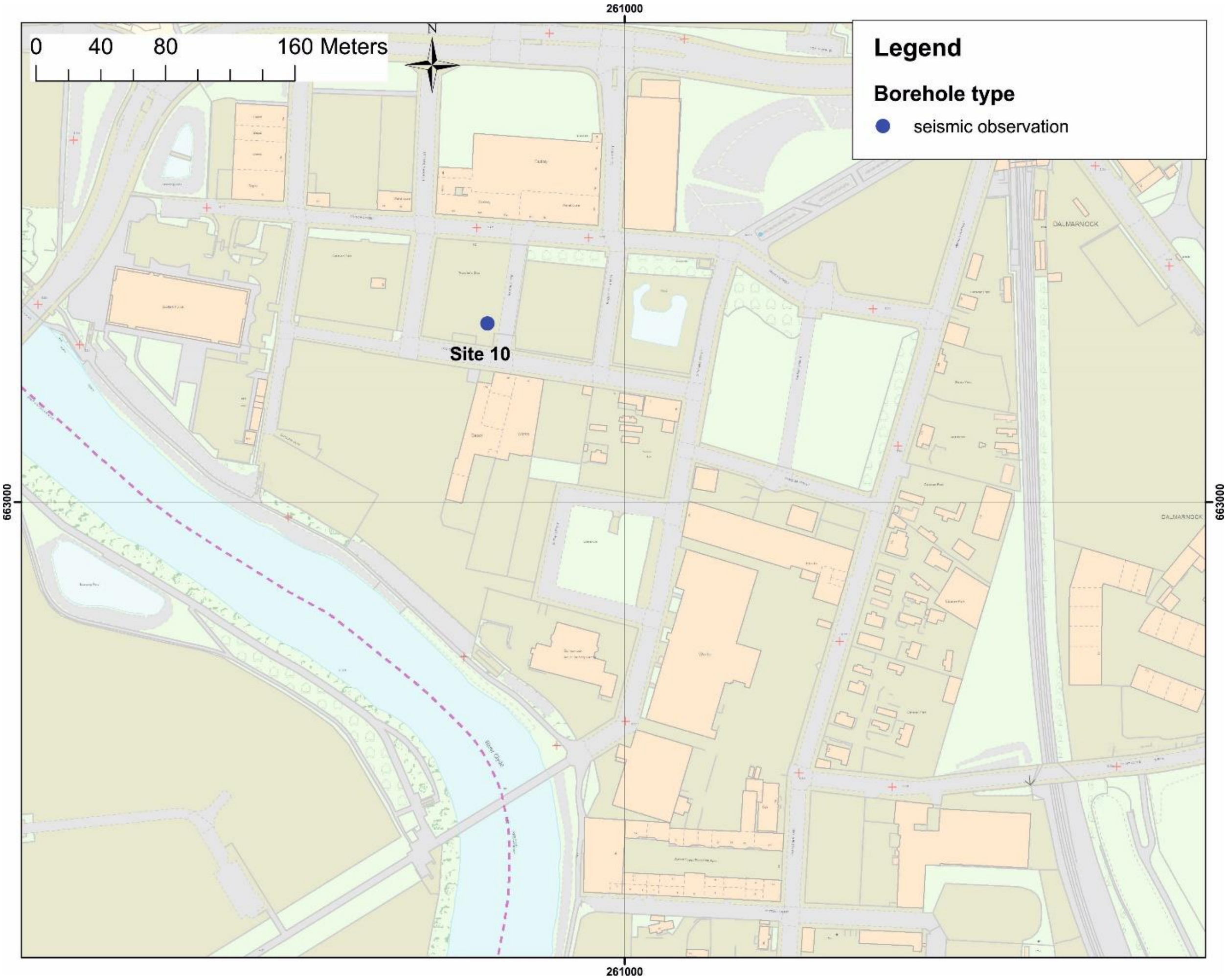

Figure 14 Array C: Seismic monitoring borehole location at Dalmarnock. Ordnance Survey data ©Crown Copyright and database rights 2018. Ordnance Survey Licence No. 100021290 EUL.

The seismic monitoring borehole is located at GGERFS10 in Dalmarnock. (Figure 14). The location was chosen due to the availability of a power and broadband connection and being at some distance from motorways and railways. At this location there are no recorded mine workings on abandonment plans. Given the presence of recorded mine workings to the east of the borehole location, it is considered possible that there are unrecorded mine workings.

4.4.3 Infrastructure

The seismic borehole will have an internal casing diameter of 76.2 mm to 199 m drilled depth. It will contain a string of 5 seismometers at depths roughly 199 m, 160 m, 120 m, 80 m and 40 m. The core will have a 101.6 mm diameter.

4.4.4 **Scientific instrumentation**

Guralp Radian broadband seismometers that record 3-component acceleration data will be lowered into the borehole via a cable and are held in place with hole locks. The seismic data will be logged at the surface and telemetered in real-time to the online data portal.

To protect the expensive seismic instrumentation, the borehole will not generally be available for the deployment of other scientific equipment.

4.4.5 **Scientific data acquisition**

UKGEOS will deliver the following data from the seismic monitoring borehole:

- Geophysical borehole logging (open hole, planned to include gamma, caliper, temperature, conductivity, density, neutron, resistivity, sonic, flowmeter, acoustic televiewer)
- Core
- It is being planned to collect time-dependent core samples for geomicrobiology studies (i.e. samples that require preservation or analysis soon after drilling)
- Continuous seismometer data

All data collected at the site will be made available to researchers.

4.5 SURFACE AND NEAR-SURFACE ENVIRONMENTAL BASELINE MONITORING EQUIPMENT

A range environmental baseline monitoring activities are planned for the research site area, both adjacent to and in the area surrounding the boreholes. Two illustrations (Figures 15, 16) are given below to give a flavour of the equipment planned.

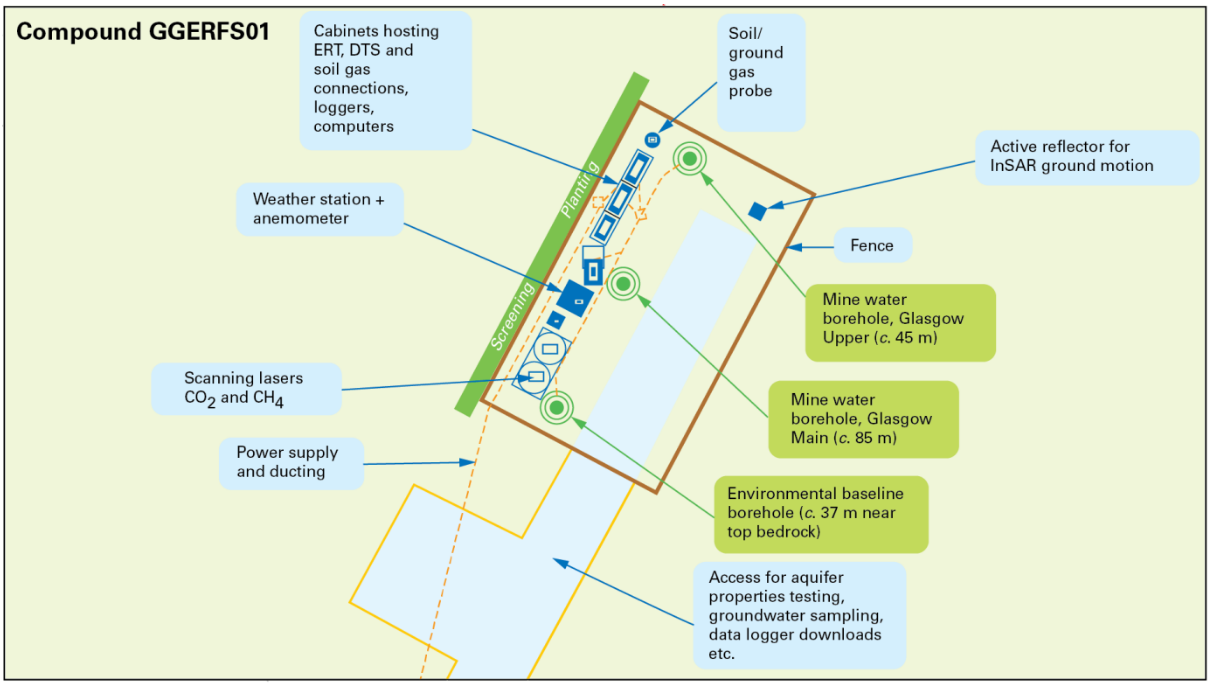

Figure 15 Image showing the planned research compound at GGERFS01.

This is the site containing the most equipment, including soil/ground gas probe, near-surface scanning lasers for CO_2 and CH_4 plus an active reflector for InSAR measurements.

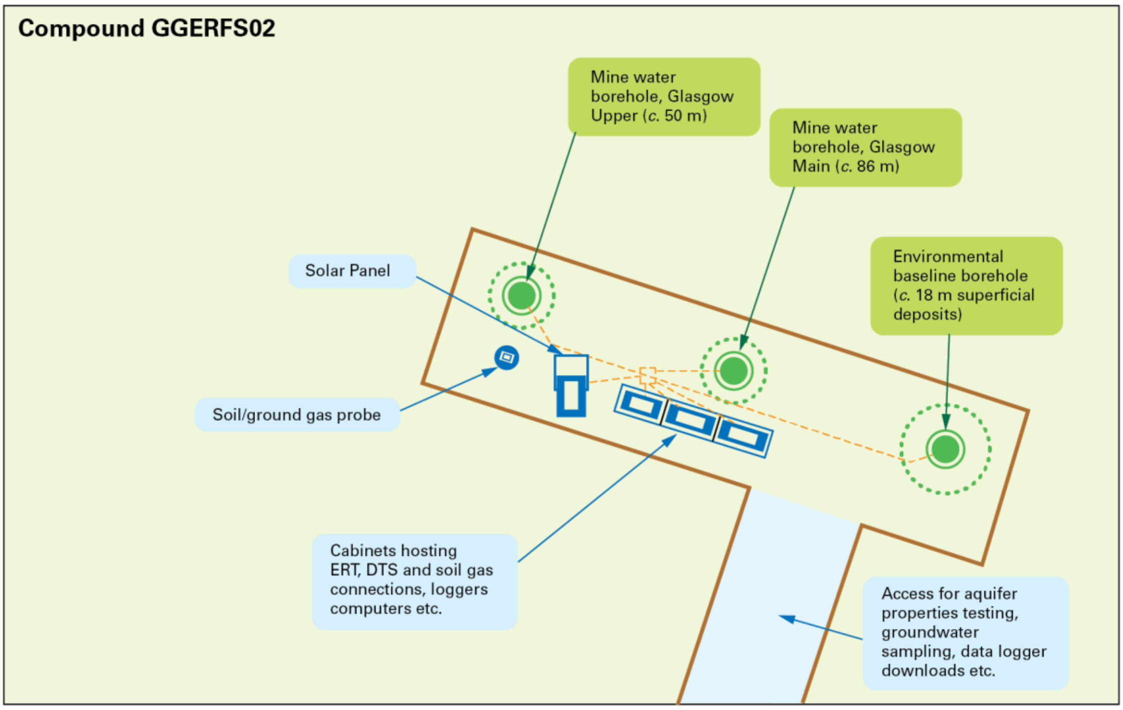

Figure 16 Image showing a typical research compound at GGERFS02.

The following sections summarise this infrastructure in more detail.

4.5.1 Ground motion

4.5.1.1 Overview

Ground motion monitoring in the Glasgow area is designed to detect the occurrence of any instability (subsidence, uplift or stability) of the target area before, during, and following subsurface research activities using Synthetic Aperture Radar (SAR) images, which have been acquired since 1995. The interferometric processing of the available SAR imagery (InSAR) has been designed to provide displacement measurements at different times with millimetre accuracy.

4.5.1.2 Location of infrastructure

Assessment of the InSAR data is ongoing over a much wider area of Glasgow than immediate boreholes sites. To improve the calibration and accuracy of future InSAR data, a passive InSAR reflector will be installed at Site 05 (Figures 11, 17) and an active InSAR reflector will be installed at Site 01 (Figure 15).

Figure 17 Passive trihedral corner reflector for SAR imagery.

4.5.1.3 Data availability

The data generated from this infrastructure includes:

- InSAR results of the average ground motion and relative time-series
- Geological interpretation of the InSAR data in order to identify the extent and origin of any possible ground movement.

4.5.2 **Soil/Ground gas**

4.5.2.1 Overview

Soil or ground gas* monitoring is essential to provide baseline data on mine gas risk at key points (e.g. near shafts, faults, where coals come to outcrop, boreholes) to detect any existing mine gas reaching the surface. It will also provide information on gases occurring from artificial ground deposits and from natural soils. The soil gas baseline study will involve a phased programme of work for monitoring/measurement of soil gas concentrations and flux and near-ground atmospheric gas concentrations to establish the environmental baseline before any research activities begin.

(*ground gas -at a depth of c. 80–100 cm, in general providing ground gas concentrations free from atmospheric dilution effects and remaining in the vadose zone)

4.5.2.2 LOCATION OF INFRASTRUCTURE

Soil gas walkover surveys were undertaken in areas including and surrounding the planned borehole compounds GGERFS01–05 in August 2018, prior to any construction activities on site. Ground gas samples were collected and flux measurements were taken

Continuously recording soil gas probes are planned for borehole Sites 01, 02, 03, and 05.

Two scanning lasers (Figure 18) are planned for Site 01 for the purpose of continuous monitoring of near surface CO_2 and CH_4.

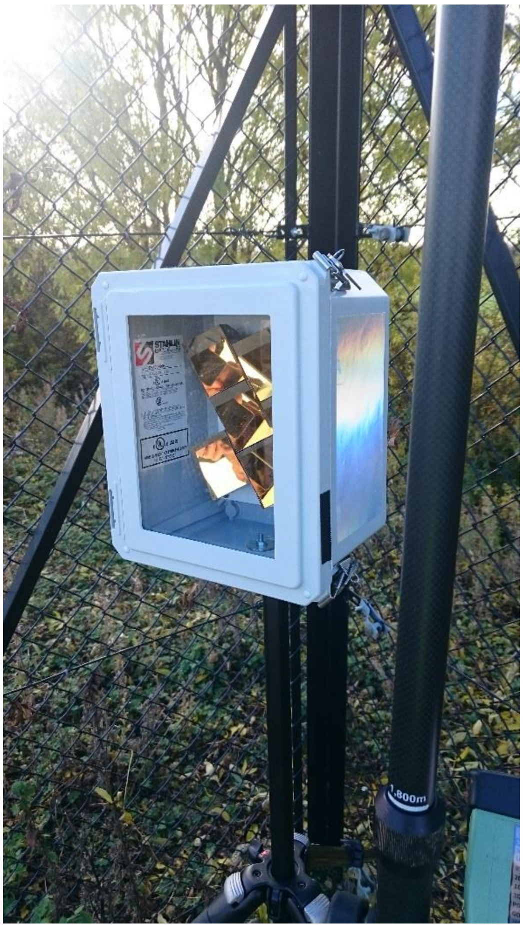

Figure 18 Scanning laser (left) and typical reflector (right).

4.5.2.3 DATA AVAILABILITY

Data from the soil gas monitoring probes will be downloaded monthly and made openly available. A continuous, live data feed is planned to be available from the scanning lasers.

4.5.3 **Soil chemistry**

4.5.3.1 OVERVIEW

A soil geochemistry monitoring programme will characterise baseline conditions and support the future science-based activities. Previous BGS soil surveys (Fordyce et al. 2012) and site investigation reports for inorganic substances and persistent organic pollutants (POPs) have indicated that there is some, highly variable land contamination in soils in the area.

Two sampling rounds are planned

(i) prior to drilling – completed in March 2018

(ii) after the ground disturbance of putting boreholes in place to establish the pre-operational soil chemistry environmental baseline

Unlike fluid chemistry, soil chemistry does not change significantly over seasonal temporal scales so future sampling is recommended after the facility has been operating for 2–3 years.

The soil quality monitoring programme aims to:

(i) improve the scientific understanding of the near-surface environment and interactions with the subsurface in the study area
(ii) support interpretation of water quality data
(iii) provide information on ground conditions; help meet regulatory requirements and provide public reassurance

4.5.3.2 LOCATION OF SAMPLES

In March 2018, ten samples were collected from 0–20 cm depth from each planned borehole site and from two control sites using locations determined for statistical validity.

4.5.3.3 DATA AVAILABILITY

Laboratory analyses of major and trace elements, pH, total organic carbon (TOC) and Cr6+ speciation, persistent organic pollutants (POPs), total petroleum hydrocarbons (TPH) and polycyclic aromatic hydrocarbons (PAH) as well as PCBs that are of environmental concern are ongoing. The data will be made openly available.

4.5.4 **Surface water**

4.5.4.1 OVERVIEW

An environmental surface water quality monitoring task will characterise baseline conditions and help direct future science-based activities. Surface water quality monitoring will be carried out alongside baseline groundwater monitoring and will take place over a minimum 12-month period starting in Autumn 2018.

The aims of the surface water monitoring programme are to:

- improve the scientific understanding of the surface water environment and groundwater-surface water interactions to aid hydrogeological model characterisation

- establish a surface water sampling network to generate benchmark information for a 12-month baseline period, including spatial and temporal variability. Against which, any future research results can be compared to identify any environmental change(s) resulting from the proposed activities.
- this could be extended to a future longer-term programme suitable for detecting environmental change resulting directly or indirectly from research activities and, potentially, other anthropogenic influences;
- contribute to the assessment and management of risks associated with geothermal resource development and help to meet regulatory requirements

4.5.4.2 Location of samples

Sample locations are limited by the small number of exposed watercourses (many are culverted) and access to them. Figure 19 shows the surface water sampling sites currently planned.

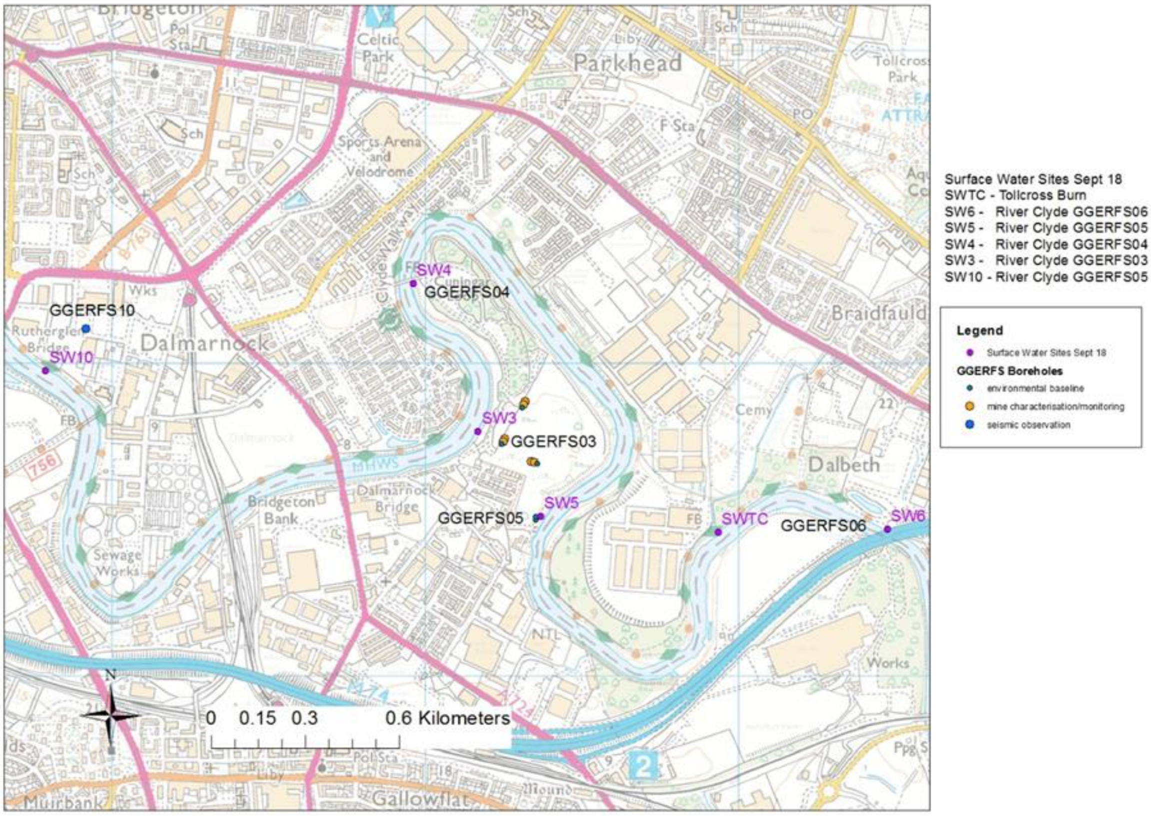

Figure 19 Surface water sampling sites currently planned, exact locations subject to change. Ordnance Survey data ©Crown Copyright and database rights 2018. Ordnance Survey Licence No. 100021290 EUL.

4.5.4.3 Data availability

The list of planned analytes is given in Appendix B. The data will be made openly available.

5 Physical collections and related data acquisition

5.1 OVERVIEW

It is envisaged that significant volumes of physical samples and data will be collected during drilling and immediately post drilling. This section reviews the types of samples and data that the British Geological Survey plan to host. The material and the data will be available to all researchers who wish to undertake research relating to UKGEOS. Future UKRI funded research will also be expected to deposit data at the National Geoscience Data Centre hosted by BGS.

5.2 DRILLING DATA

During drilling, a wide range of operational data will be collected. These data include drillers' logs and drilling parameters.

5.3 CORE MATERIAL

Core material is a key dataset for characterising the geology. One core of around 190 m is planned in a representative section of the Coal Measures Group stratigraphy.

The core will be sampled for geomicrobiological analysis near site and then transported to BGS Keyworth. To facilitate biological sampling a tracer will be added to drilling fluid at certain intervals to assess contamination of samples. Fluorescent microspheres or other chemical tracers will be used for the assessment of infiltration of drill mud into the sample core.

The core will be logged for lithology and fractures and will be described and interpreted to provide detailed insight into the stratigraphic evolution of the area and the depositional environments.

The core will be scanned using the full suite of core scanning equipment documented in Appendix A.

The core material will be stored in the BGS Keyworth core store, where it will be available for researchers to view and undertake further sampling/research.

5.4 WIRELINE LOGGING

Geophysical logging will provide rock property information and assist in stratigraphic logging. The seismic monitoring borehole is intended to be logged as open hole with suite of tools including gamma, caliper, density, neutron, resistivity, sonic, flowmeter. Other geophysical logging will be a limited suite of cased hole logs (gamma, caliper) in the deepest mine water boreholes at Sites 01, 02 and 03.

5.5 PHYSICAL CORE SAMPLE ANALYSIS

Physical core will be analysed for a range of microbiological, geochemical and geomechanical properties. The core will be available for researchers to undertake further analysis. All data will be available openly.

The BGS planned core analyses include

- Time dependent geomicrobiology sampling
- Core scanning

5.6 GROUNDWATER AND FLUID SAMPLES

Plans for sampling core and cuttings material, plus groundwater and other fluids (drilling fluids, gases etc.) are described in an overview sampling plan (*UKGEOS report G0007*).

6 UKGEOS data portal

6.1 OVERVIEW

The UK Geoenergy Observatories informatics platform will provide the infrastructure necessary to collect, transmit and store data from the field as well as provide researchers with the necessary tools to discover, access and process such data. It will:

- allow data (real-time or otherwise) collected in the field to be streamed back to scientists and/or web portals
- store scientific data in bespoke databases
- facilitate re-use and sharing of scientific data between scientists
- allow for expansion as demand requires (e.g. allowing data from new experiments to be streamed to the portal)
- be supported long-term by BGS data and system management
- provide access to new NERC facilities such as a suite of core scanners.

6.2 ACCESS TO NEAR REAL-TIME AND/OR CONTINUOUS ENVIRONMENTAL BASELINE DATA

The informatics platform will initially be used to transmit near real-time and/or continuous (monthly downloaded) data from environmental monitoring sensors to scientists, businesses and the public through web-based delivery channels. These data will characterise the subsurface around the research facility before any scientific experiments take place.

Once research commences, scientists will be able to use this infrastructure to transmit continuous data from their experiments back to the laboratory. Data will be presented publicly via dedicated data portals, providing audience-tailored views including spatial and temporal visualisations as well as search, query and download tools. The portals will be developed in advance of the baseline monitoring taking place so that they can be launched as soon as data streams from the field go live. Links to these new facilities will be published on the BGS website and in other appropriate communication channels.

7 ACCESS TO SITE CHARACTERISATION AND SCIENTIFIC DATA

In addition to temporal data streams, the informatics platform will provide public access to other key datasets including, but not limited to:

- borehole data such as physical samples, imagery and geophysical analysis
- 2D maps and 3D models of geological properties and structures

- remote-sensing data
- laboratory analysis results
- numerical models of fluid-flow processes
- immersive visualisations of diverse datasets

The informatics platform will also provide long-term storage of scientific data collected at the site.

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.

BANKS, D, FRAGA PUMAR, A, AND WATSON, I. 2009. The operational performance of Scottish minewater-based ground source heat pump systems. *Quarterly Journal of Engineering Geology and Hydrogeology*, 42, 347–357. doi:10.1144/1470-9236/08-081

BAPTIE, B, SEGOU, M, ELLEN, R, AND MONAGHAN, A A. 2016. Unconventional Oil and Gas Development: Understanding and Monitoring Induced Seismic Activity. *British Geological Survey Open Report*, OR/16/042. 92pp. Available from https://beta.gov.scot/publications/unconventional-oil-gas-understanding-monitoring-induced-seismic-activity/

BATESON, L, NOVELLINO, A, AND JORDAN, C. 2018. Glasgow Geoenergy Research Field Site -Ground motion survey report. *British Geological Survey Open Report* OR/18/054 (currently in review)

BIANCHI, M, KEARSEY, T, AND KINGDON, A. 2015. Integrating deterministic lithostratigraphic models in stochastic realizations of subsurface heterogeneity. Impact on predictions of lithology, hydraulic heads and groundwater fluxes. *Journal of Hydrology*, 531 (3). 557–573. 10.1016/j.jhydrol.2015.10.072

BRITISH GEOLOGICAL SURVEY, 2007. 1:10,000 scale bedrock map of NS66SW.

BRITISH GEOLOGICAL SURVEY, 2007. 1:10,000 scale superficial deposits map of NS66SW.

BURLEY, A J, EDMUNDS, W M. AND GALE, I N. 1984. Investigation of the geothermal potential of the UK : catalogue of geothermal data for the land area of the United Kingdom. Br*itish Geological Survey, 161pp.* (WJ/GE/84/020) (Unpublished)

HALL, I H S, BROWNE, M A E, AND FORSYTH, I H. 1998. Geology of the Glasgow district. *Memoir of the British Geological Survey,* Sheet 30E (Scotland). ISBN 0-11-884534-9.

FORDYCE, F M, NICE, S E, LISTER, T R, Ó DOCHARTAIGH, B É, COOPER, R, ALLEN, M, INGHAM, M, GOWING, C, VICKERS, B P, AND SCHEIB, A. 2012. Urban Soil Geochemistry of Glasgow. *British Geological Survey Open Report* OR/08/002. http://nora.nerc.ac.uk/18009/

FORDYCE, F M, Ó DOCHARTAIGH, B É, LISTER, T R, COOPER, R, KIM, A, HARRISON, I, VANE, C, AND BROWN, S E. 2004. Clyde Tributaries: Report of Urban Stream Sediment and Surface Water Geochemistry for Glasgow. *British Geological Survey Commissioned Report* CR/04/037. http://nora.nerc.ac.uk/18996/

KEARSEY, T, WILLIAMS, J, FINLAYSON, A, WILLIAMSON, P, DOBBS, M, MARCHANT, B, KINGDON, A AND CAMPBELL, S.D. 2015 Testing the application and limitation of stochastic simulations to predict the lithology of glacial and fluvial deposits in Central Glasgow, UK. *Engineering Geology*, 187. 98 - 112. 10.1016/j.enggeo.2014.12.017

Kearsey, T I, Whitbread, K, Arkley, S L B, Finlayson, A, Monaghan, A A, McLean, W S, Terrington, R L, Callaghan, E, Millward, D and Campbell, S D G. In press. Creation and delivery of a complex 3D geological survey for the Glasgow area and its application to urban geology. *Earth and Environmental Science: Transactions of the Royal Society of Edinburgh.*

Kearsey T. and Burkin J. 2018. Model metadata report for the GGERFS initial bedrock model *BGS Open Report OR/18/053* (currently in review)

Kim, A W, Vane, C H, Moss-Hayes, V L, Beriro, D J, Nathanail, C P, Fordyce, F M, and Everett, P A. In Press. Polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB) in urban soils of Glasgow, UK. *Earth and Environmental Science: Transactions of the Royal Society of Edinburgh*

Kingdon, A, Dearden, R A and Fellgett, M W., 2018. UK Geoenergy Observatories, Cheshire Energy Research Field Site, Science Infrastructure, British Geological Survey Open Report, UK Geoenergy Observatories Programme, OR/18/05

Monaghan, A A, Arkley, S L B, Whitbread, K, and McCormac, M. 2013. Clyde superficial deposits and bedrock models released to the ASK Network 2014: a guide for users Version 3. *British Geological Survey Open Report, OR/14/013.* 35pp. http://nora.nerc.ac.uk/id/eprint/505554/

Monaghan, A A, Ó Dochartaigh, B, Fordyce, F, Loveless, S, Entwisle, D, Quinn, M, Smith, K, Ellen, R, Arkley, S, Kearsey, T, Campbell, SDG, Fellgett, M, and Mosca, I. 2017. UKGEOS - Glasgow Geothermal Energy Research Field Site (GGERFS): Initial summary of the geological platform. *British Geological Survey Open Report, OR/17/006*. 205pp. http://nora.nerc.ac.uk/id/eprint/518636/

Ó Dochartaigh, B É, Smedley, P L, MacDonald, A M, Darling, W G, and Homoncik, S. 2011. Baseline Scotland: groundwater chemistry of the Carboniferous sedimentary aquifers of the Midland Valley. *British Geological Survey Open Report* OR/11/021. http://nora.nerc.ac.uk/id/eprint/14314/

Ó Dochartaigh, B E, MacDonald, A M, Fitzsimons, V, and Ward, R. 2015. Scotland's aquifers and groundwater bodies. Nottingham, UK, *British Geological Survey OR/15/028, 63pp.* http://nora.nerc.ac.uk/id/eprint/511413/

Ó Dochartaigh, B É, Bonsor, H C, and Bricker, S H. 2018 in press. The Quaternary groundwater system in Glasgow UK. *Earth and Environmental Science: Transactions of the Royal Society of Edinburgh.*

Ramboll for GGERFS planning application for South Lanarkshire Council, 2018a. GLASGOW GEOTHERMAL ENERGY RESEARCH FIELD SITE: CUNINGAR LOOP, GGERFS01-05 PHASE I ENVIRONMENTAL REVIEW. Available online at https://publicaccess.southlanarkshire.gov.uk/online-applications/caseDetails.do?caseType=Application&keyVal=P7OTP9OPHQJ00

Ramboll for GGERFS planning application for South Lanarkshire Council, 2018b. UK GEOENERGY OBSERVATORIES: GLASGOW GEOTHERMAL ENERGY RESEARCH FIELD SITE ENVIRONMENTAL REPORT. Available online at https://publicaccess.southlanarkshire.gov.uk/online-applications/caseDetails.do?caseType=Application&keyVal=P7OTP9OPHQJ00

Ramboll for GGERFS planning application for Glasgow City Council, 2018c. GLASGOW GEOTHERMAL ENERGY RESEARCH FIELD SITE: DALMARNOCK, GGERFS10 PHASE I ENVIRONMENTAL REVIEW. Available online at https://publicaccess.glasgow.gov.uk/online-applications/applicationDetails.do?keyVal=P70V2DEXFH600&activeTab=summary

Ramboll for GGERFS planning application for Glasgow City Council, 2018d. UK GEOENERGY OBSERVATORIES: GLASGOW GEOTHERMAL ENERGY RESEARCH FIELD SITE ENVIRONMENTAL REPORT. Available online at https://publicaccess.glasgow.gov.uk/online-applications/applicationDetails.do?keyVal=P70V2DEXFH600&activeTab=summary

Rollin, K E. 1987. Catalogue of geothermal data for the land area of the United Kingdom. Third revision: April 1987. Investigation of the geothermal potential of the UK, British Geological Survey, Keyworth.

SMEDLEY, PL, BEARCOCK, J M, FORDYCE, FM, EVERETT, PA, CHENERY, S, AND ELLEN, R. 2017. *Stream-water geochemical atlas of the Clyde Basin.* Nottingham, UK, British Geological Survey, 168pp. (OR/16/015) http://nora.nerc.ac.uk/id/eprint/519332/

TURNER, R J, MANSOUR, M M, DEARDEN, R, O DOCHARTAIGH, B E, AND HUGHES, A G. 2015. Improved understanding of groundwater flow in complex superficial deposits using three-dimensional geological-framework and groundwater models: an example from Glasgow, Scotland (UK). *Hydrogeology Journal* Vol 23 (3), 493-506

WILLIAMS, J.D.O., DOBBS, M.R., KINGDON, A., LARK, R.M., WILLIAMSON, J.P., MACDONALD, A.M. Ó DOCHARTAIGH, B.É. In press. Stochastic modelling of hydraulic conductivity derived from geotechnical data; an example applied to Central Glasgow. Earth and Environmental Science, Transactions of the Royal Society of Edinburgh journal.

YOUNGER, P L, AND ROBINS, N S. 2002. Challenges in the characterisation and prediction of the hydrogeology and geochemistry of mined ground. In *Mine Water Hydrogeology and Geochemistry*. Younger PL and Robins NS (editors). Geological Society of London Special Publication, No. 198, 1–16.

Appendix A: Working at UKGEOS

A.1 OVERVIEW

The UKGEOS Glasgow Geothermal Energy Research Field Site is open to researchers from the UK and internationally. Researchers both from academia and from industry are welcome. Each set of boreholes will be within an accessible research compound that also contains environmental baseline monitoring equipment.

A.2 ON-SITE FACILITIES

The research facilities will be limited to the borehole compounds. Within the urban area, there are a range of food, drink and welfare facilities nearby. Currently there are no dedicated laboratory facilities, though there are a number of universities and laboratories nearby.

A.3 SCIENCE FACILITIES

A.3.1. Borehole compounds

An illustration of two of the 'research phase' borehole compounds is given above (Figures 15, 16). Access to the boreholes for sampling and experimentation will be managed by a research steering committee and operated by BGS.

A.3.2 Core viewing facilities

Core examination laboratories are available to use at BGS Keyworth.

A.3.3. Core scanning facilities

A new, state-of the art, core scanning facility funded by UKGEOS is available as part of the National Geological Repository (NGR) at Keyworth, Nottingham, UK. The NGR Core Scanning Facility hosts several high-resolution core scanners (e.g. Figure 20) that allow whole, split, or slabbed rock and sediment cores to be, continuously and non-destructively, scanned before being further processed. Core scanning provides detailed information on the geophysical, mineralogical, and geochemical characteristics of the core, records core quality and fundamental variations downcore, and allows high-definition optical, near-infrared (NIR), ultraviolet (UV), and X-radiographic images to be taken.

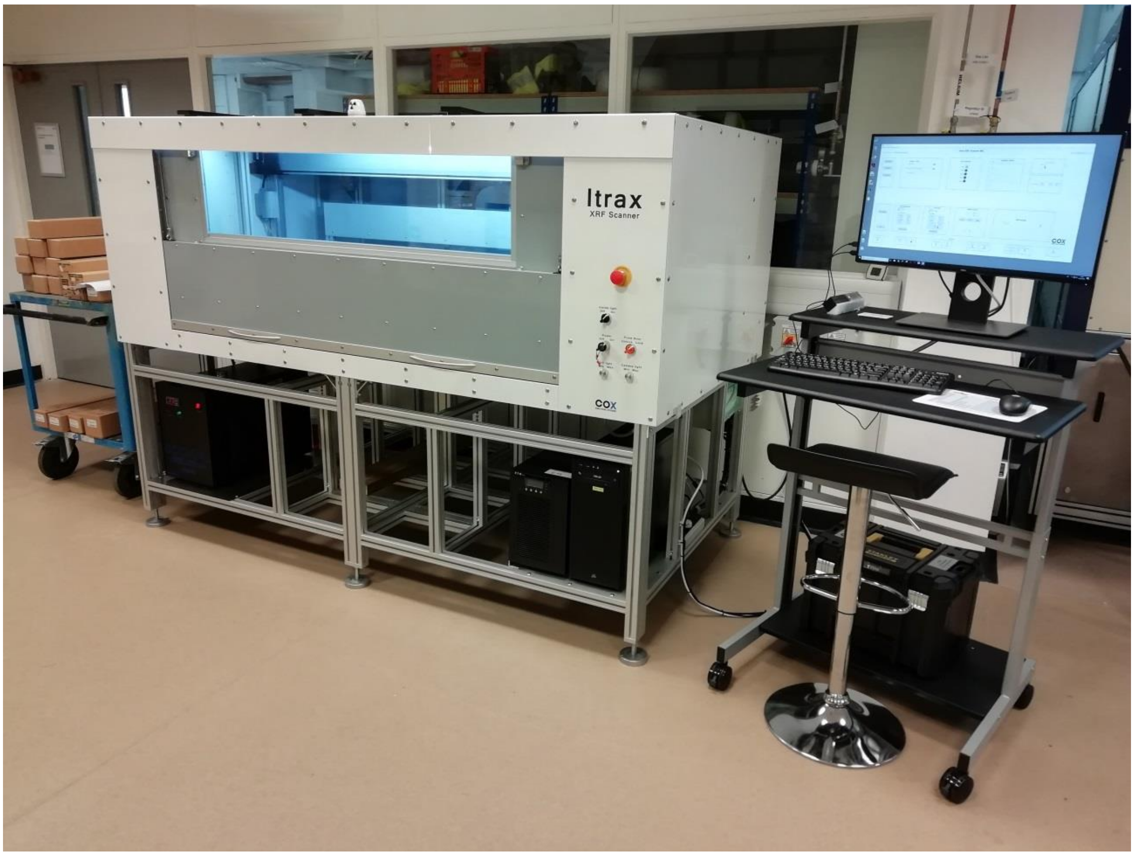

Figure 20 Itrax XRF core scanner at BGS Keyworth.

The following core scanning facilities are available:

- **X-ray tomography** – Rotating X-ray computed tomography visualises and records internal structures present within the core to determine core quality, heterogeneity and fracture networks.
- **Geophysics and core imaging** – Multi-sensor core logging providing ultra-high definition core images and geophysical analyses, including:
    - bulk density, porosity, salinity, and/or P-wave velocity profiles
    - core quality, heterogeneity, and lithology variations (e.g., grain-size, texture, colour)
    - estimations of water content and permeability
    - compositional changes etc.

- **X-ray fluorescence scanners –** These acquire elemental abundances and variations downcore, and produce 2D XRF maps. XRF scanning is a well-established, non-destructive method that allows:
    - Characterisation of rock and sediment provenances
    - Interpretation of mineralogy and matrix properties etc.

A.4 HEALTH AND SAFETY

Users of the research facility will be required to follow site Health and Safety procedures.

A.5 RESEARCH ACCESS

Longer term arrangements for research access are being discussed and are likely to involve application to a facilities steering committee.

Early facility access for time-dependent and construction to early baseline monitoring phase sampling, plus installation of infrastructure during the construction phase will be organised via

- A workshop open to the science community
- A call for applications from BGS
- An early facility access form
- A small committee to judge on scientific merit, practicality and cost/time implications
- Funding for early facility access is NOT in place.

The NERC data policy will apply to research use of the facility

A.6 COMMERCIAL ACCESS

Commercial access is likely to involve payment of a fee for use of the facility. Costs and terms of access will be available in due course.

Appendix B Table of analytes proposed for BGS baseline groundwater analyses

Groundwater	Units
HCO_3	mg/L
ORP	mV
pH	
SEC	µs/cm
Temp	°C
Dissolved Oxygen	mg/L
H_2S and other gas meter at site	%
CH_4	mg/L
CO_2	mg/L
Rn	Bq/L
CFC	pmol/L

Groundwater	Units
SF_6	pmol/L
Noble Gases He, Ne, Ar, Kr, Xe	cm^3 STP/ L
NPOC	mg/L
TIC	mg/L
δ^2H	0/00
$\delta^{18}O$	0/00
$\delta^{13}C$	0/00
Cr^{6+} Speciation	µg/L
TPH:	
TPH (C10-C40)	mg/L
TPH (C8-C10)	mg/L
TPH (C8-C40)	mg/L
PAH:	
Benzo (a) pyrene	µg/L
Benzo (b) fluoranthene	µg/L
Benzo (ghi) perylene	µg/L
Benzo (k) fluoranthene	µg/L
Indeno (1,2,3-cd) pyrene	µg/L
PAH - total	µg/L
VOC:	
Benzene	µg/L
Carbon tetrachloride	µg/L
Chloroform	µg/L
1,2 Dichlorobenzene	µg/L
1,3 Dichlorobenzene	µg/L
1,4 Dichlorobenzene	µg/L
1,2 Dichloroethane	µg/L
Dichloromethane	µg/L
Ethylbenzene	µg/L
m/p-Xylene	µg/L
MTBE	µg/L
o-Xylene	µg/L
Tetrachloroethene	µg/L
Toluene	µg/L
Trichloroethene	µg/L
1,1,1 Trichloroethane	µg/L
Br	mg/L
Cl	mg/L
F^-	mg/L
HPO_4	µg/L
NO_2	mg/L
NO_3	mg/L
SO_4	mg/L
I	µg/L
NH_4	mg/L
HCO_3 lab	mg/L
Ag	µg/L

Groundwater	Units
Al	µg/L
As	µg/L
B	µg/L
Ba	µg/L
Be	µg/L
Bi	µg/L
Ca	mg/L
Cd	µg/L
Ce	µg/L
Co	µg/L
Cr	µg/L
Cs	µg/L
Cu	µg/L
Dy	µg/L
Er	µg/L
Eu	µg/L
Fe	µg/L
Ga	µg/L
Gd	µg/L
Hf	µg/L
Ho	µg/L
K	mg/L
La	µg/L
Li	µg/L
Lu	µg/L
Mg	mg/L
Mn	µg/L
Mo	µg/L
Na	mg/L
Nb	µg/L
Nd	µg/L
Ni	µg/L
P	mg/L
Pb	µg/L
Pr	µg/L
Rb	µg/L
Rh	µg/L
Ru	µg/L
S (total)	mg/L
Sb	µg/L
Se	µg/L
Si	µg/L
Sm	µg/L
Sn	µg/L
Sr	µg/L
Ta	µg/L
Tb	µg/L

Groundwater	Units
Th	µg/L
Ti	µg/L
Tl	µg/L
Tm	µg/L
U	µg/L
V	µg/L
W	µg/L
Y	µg/L
Yb	µg/L
Zn	µg/L
Zr	µg/L

Table 4 Table of analytes proposed for groundwater characterisation