



Drilling into mines for heat: geological synthesis of the UK Geoenery Observatory in Glasgow and implications for mine water heat resources

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Abstract: Thermal energy from groundwater in abandoned, flooded, coal mines has the potential to make a significant contribution to decarbonization of heat and net-zero carbon emissions. In Glasgow, UK, a subsurface observatory has been constructed for mine water heat and heat storage research. We synthesize geological and mine water resource findings from a 4 year period of borehole planning, drilling, logging and testing. The heterogeneous bedrock is typical of the Scottish Coal Measures Group, whereas superficial deposits are more sand- and gravel-dominated than predicted. Mine water boreholes encountered workings in the Glasgow Upper, Glasgow Ell and Glasgow Main coal seams, proving water-filled voids, mine waste, fractured rock mass and intact coal pillars, with high yields on initial hydrogeological testing. Although the depth and extent of mine workings delineated on mine abandonment plans proved accurate, metre-scale variability was expected and proved in the boreholes. A mine water reservoir classification established from the observatory boreholes highlights the resource potential in areas of total extraction, stowage, and stoop and room workings. Because their spatial extent is more extensive across the UK than shafts or roadways, increasing the mine water energy evidence base and reducing exploration risk in these types of legacy workings is important.

Supplementary material: Borehole reports and other datasets are available at <https://ukgeos.ac.uk/data-downloads> (mixture of over 20 DOI datasets and reports or data packs published openly on <https://nora.nerc.ac.uk>; all material is deposited in the National Geoscience Data Centre).

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Net-zero carbon emissions targets require significant progress to be made in the decarbonization of heat. UK and devolved Government policy has shifted to meet net-zero targets by 2050 or earlier (e.g. [HM Government 2018, 2020](#); [CCC 2019](#); [Scottish Government 2020](#)) and although significant progress has been made in the decarbonization of electricity ([HM Government 2020](#)), decarbonization of heat presents a more difficult policy and implementation challenge ([Abesser 2020](#); [Parliamentary Office of Science and Technology 2020](#)). For example, in 2019 48 GW of renewable electricity capacity was available in the UK, representing 37% of generation, whereas 90% of homes used fossil fuels for heating, cooking and hot water ([HM Government 2020](#)) with peak heat demand calculated at 170 GW ([Watson *et al.* 2019](#)). In 2020, the UK Government's energy White Paper included major ambitions to transform heating of homes to clean energy sources including a target of installation of 600 000 heat pumps a year by 2028 ([HM Government 2020](#)). However, the value of the subsurface for decarbonization needs to be better understood by decision-makers, progressing by delivering scaled-up pilot schemes, independent environmental monitoring and improved characterization ([Stephenson *et al.* 2019](#)). Geothermal energy and subsurface heat storage have significant potential for delivering low-carbon heat. Low-enthalpy 'shallow geothermal' heat recovery from and seasonal thermal storage in abandoned coal mines offers one such opportunity ([Gluyas *et al.* 2018](#); [Adams *et al.* 2019](#); [Stephenson *et al.* 2019](#)).

Many of the UK's towns and cities are underlain by abandoned coal mines. Upon closure and with the cessation of dewatering, the mines have become naturally flooded with groundwater. The mine

workings and rock mass surrounding them have a higher permeability compared with unmined rock owing to still-open and partially collapsed mined voids and collapse-related fractures forming an 'anthropogenically enhanced aquifer'. [Banks *et al.* \(2004, 2009, 2017\)](#) and others have documented that mine water can be abstracted through a borehole and passed through a heat exchanger and heat pump to provide space heating and cooling for homes and businesses, before being returned within a sealed loop to a different part of the mine system via a second borehole ([Fig. 1](#)). Important factors for mine water heat resources include the presence and connectivity of flooded, abandoned mine workings, groundwater flow directions and recharge, pumping rate information, temperature, water levels and chemistry (e.g. [Ramos *et al.* 2015](#); [Loredo *et al.* 2016](#); [Banks *et al.* 2017](#); [Farr *et al.* 2020](#)), as well as land availability and heat demand. Flooded mine workings can act as a thermal reservoir, with the potential to provide both heat recovery and heat storage, as required. The legacy of coal mining can thus be turned into a sustainable opportunity for low-carbon heating.

Small numbers of successfully operating mine water geothermal and heat storage schemes have proved the concept of using this decarbonized energy source for heating and cooling of buildings (e.g. [Springhill, Canada, Jessop 1995](#); USA, [Watzlaf and Ackman 2006](#); [Heerlen, Netherlands, Verhoeven *et al.* 2014](#); [Asturias, Spain, Loredo *et al.* 2016](#); UK, [Banks *et al.* 2017](#); [Lanchester Wines, <https://www.lanchesterwines.co.uk/what-we-do/sustainability/>](#)).

An increasing number of mine water energy schemes are in exploration and operational stages in the UK (e.g. [Athresh *et al.* 2015](#); [Banks *et al.* 2017](#); [Brabham *et al.* 2019](#); [Coal Authority 2020](#)).

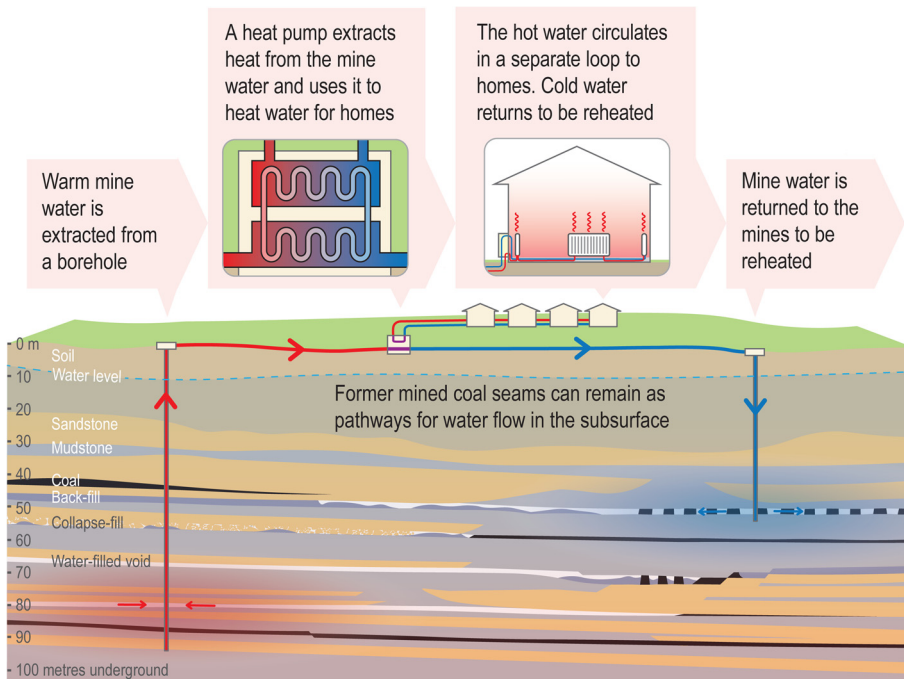


Fig. 1. Simplified overview of abandoned, flooded coal mines in the subsurface utilized for shallow, low-enthalpy mine water heat via abstraction and re-injection of groundwater, to heat homes and businesses. ©BGS, UKRI 2021.

However, the very large resource potential (e.g. Gillespie *et al.* 2013; Preece and Younger 2014; Ramos *et al.* 2015; Bailey *et al.* 2016; Farr *et al.* 2016; Gluyas *et al.* 2019) has yet to be widely exploited. Commercial demonstration of mine water heat technology is critical in breaking economic, regulatory, awareness and acceptance barriers to this widespread utilization (NERC *et al.* 2019), although making the business case can be challenging (Townsend *et al.* 2021), especially with uncertainty over support mechanisms and policy (e.g. the Renewable Heat Incentive). Underpinning geoscientific research and innovation is essential, for enhancing process understanding, providing an open evidence base towards social acceptance, defining cost models and reducing risk (NERC *et al.* 2019; Stephenson *et al.* 2019). As one of a growing number of underground laboratories worldwide, the UK Geogeneity Observatory in Glasgow ('Glasgow Observatory', Fig. 2) is a unique facility for investigating shallow, low-temperature mine water thermal energy resources in abandoned and flooded workings at depths of around 50–85 m, together with baseline and induced environmental change.

The scientific rationale for the Glasgow Observatory is multifaceted. Experiences of existing mine water energy schemes raise a number of technical challenges such as clogging and precipitation of pipe work, pumps and heat equipment (Banks *et al.* 2004, 2009; Gzyl *et al.* 2019), resource sustainability, thermal and chemical breakthrough (Preece and Younger 2014; Verhoeven *et al.* 2014; Burnside *et al.* 2016a, b) and optimal arrangements for abstraction–re-injection (Preece and Younger 2014; Banks *et al.* 2017). Regulatory approvals and public engagement require an improved knowledge base on subsurface and surface environmental monitoring and impacts (e.g. Preece and Younger 2014, 'environmental and regulatory risk'); for example, on the groundwater and surface water chemistry impacts (Banks *et al.* 2009; Burnside *et al.* 2016a, b), stability of mine workings (Younger 2014; Todd *et al.* 2019) or potential movement of mine gas (Younger 2014). As an infrastructure designed for these kinds of mine energy challenges, the Glasgow Observatory comprises 12 boreholes, four research compounds, surface monitoring equipment and open data (Monaghan *et al.* 2019).

Although Dennehy *et al.* (2019) have provided a comprehensive overview of drilling into abandoned mine workings, there is a paucity of literature on the exploration and uncertainties of drilling into highly variable legacy workings for mine water heat resources. Pre-drill predictions of the state of collapse of a mine working and

mine water reservoir (void, waste, fractured rock, intact coal) at a specific location are difficult to make from legacy data, and are likely to vary on a metre scale, yet these factors are critical as they strongly influence the hydraulic properties (e.g. Younger and Robins 2002) that are vital for the mine water resource and its sustainability. In addition, Andrews *et al.* (2020a) have illustrated sedimentation of coal breccias and laminated muds resulting from groundwater flow within a collapsing pillar and stall mine working, highlighting an additional time-dependent process that affects hydraulic properties of legacy mines and potential mine water resources. Thus, although mine workings are commonly well mapped at abandonment, the knowledge base on how their condition has evolved since flooding is limited, with likely consequences for hydraulic connectivity and sustainable hydraulic yields.

Construction of the Glasgow Observatory provides a pre-drill to post-drill exemplar. This paper synthesizes and interprets geological and borehole data through the exploration and appraisal stages and provides a basic characterization of the anthropogenically altered rock mass, including a mine water reservoir classification.

Description of the Glasgow Observatory

The Observatory is located in an urban setting in Glasgow City and South Lanarkshire (Fig. 2), with commonalities in its coal mining history, geology and legacy of industrial land use with other parts of the UK and beyond. It has proceeded through a 4 year exploration and appraisal workflow (Fig. 3; Starcher *et al.* 2021) and is at the scale of a small mine energy scheme, such as might supply a municipal or industrial building. Designed to anticipate future research, the infrastructure offers flexibility to test response to induced changes of flow, heat, etc. that would not be possible within commercial schemes.

The majority of the Glasgow Observatory infrastructure is located at Cuningar Loop, Rutherglen (Fig. 2, Table 1). Five boreholes are screened across the Glasgow Upper or Glasgow Main mine working or coal (Fig. 4, Table 1) to depths of around 50 and 85 m respectively (Barron *et al.* 2020a, b; Monaghan *et al.* 2020a, b; Starcher *et al.* 2020a, b). The boreholes are arranged in a triangle to characterize depth and spatial variability in three dimensions over tens to hundreds of metres (Fig. 2). A sixth borehole (GGA02) was drilled as a mine water borehole but encountered problems in the

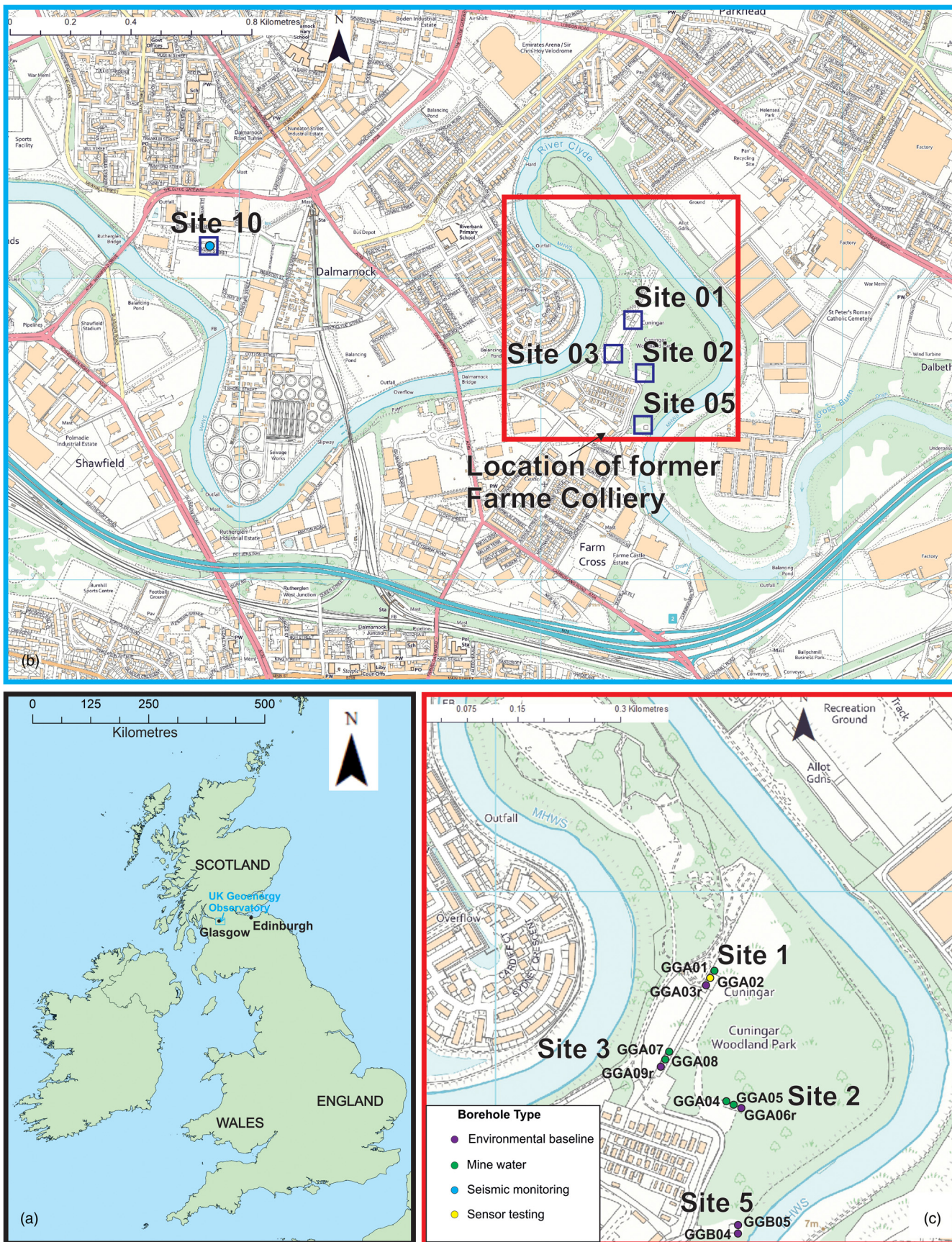


Fig. 2. (a) Location of the Glasgow Observatory in the UK; (b) position of Observatory sites; (c) detail of Cuningar Loop mine water and environmental baseline characterization and monitoring boreholes. Ordnance Survey data ©Crown Copyright and database rights 2021. Ordnance Survey Licence No. 100021290 EUL.

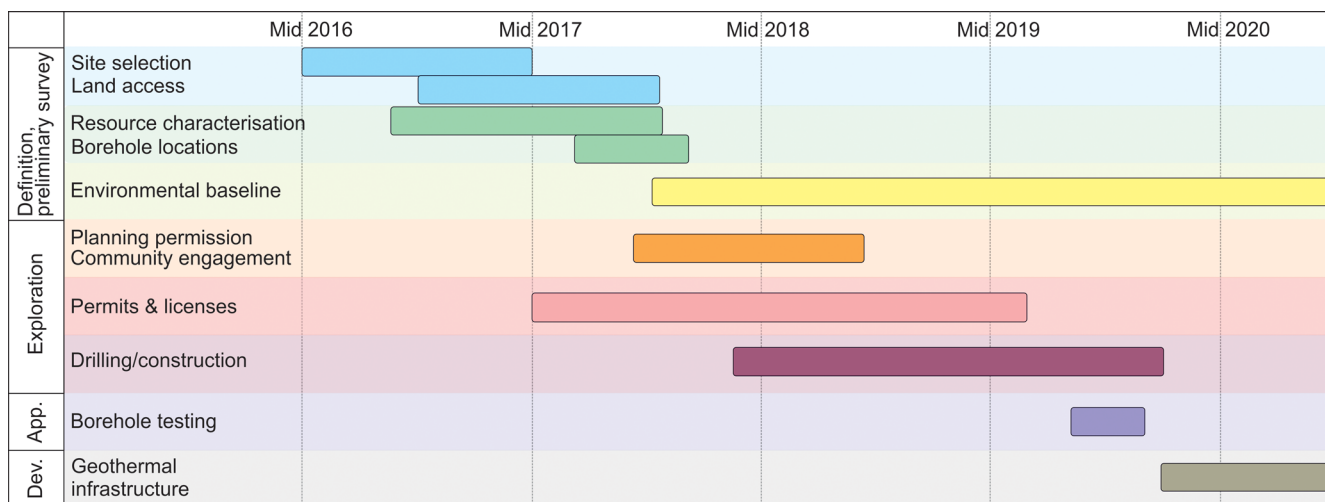


Fig. 3. Simplified timeline of the definition and preliminary survey, exploration, appraisal (App.) and start of development (Dev.) stages of the mine water heat research infrastructure of the Glasgow Observatory.

final stages of construction and is now a cased, sensor testing borehole to around 67 m depth (Monaghan *et al.* 2020c). The mine water boreholes are equipped with sensors for time-series monitoring of the subsurface. Downhole electrical resistivity tomography (ERT) sensors (Fig. 5), fibre-optic cables for distributed temperature sensing (DTS) and hydrogeological data loggers have started to allow time-series monitoring to characterize physical, chemical and flow heterogeneities. Permanent infrastructure for the abstraction and re-injection of mine water and extraction or storage of heat is planned to be installed in four of the mine water boreholes in 2021.

Five boreholes at Cuningar Loop with drilled depths between 16 and 45 m are screened in shallow superficial deposits and bedrock above the Glasgow Upper mine working (Fig. 4, Table 1; Elsome *et al.* 2020; Shorter *et al.* 2020a, b; Walker-Verkuil *et al.* 2020a, b). The boreholes record continuing baseline environmental change, will provide evidence of any impacts from pumping mine water and give an opportunity for developing new monitoring technologies. The boreholes are located in four fenced research compounds that provide space for the handling of borehole equipment and operation of surface monitoring systems (Sites 1, 2, 3 and 5; Figs 2 and 5).

The deepest borehole at the Glasgow Observatory is a 199 m cored, unmined reference section at Dalmarnock, some 1.5 km WNW of Cuningar Loop (Fig. 2). The borehole was geophysically logged and imaged and core-scans are available (Kearsey *et al.* 2019a). This borehole was fully cased in early 2019 and a string of five downhole seismometers provide baseline monitoring, feeding into the UK national seismic monitoring network. Baseline environmental monitoring of soil chemistry, soil gas, ground motion, surface water and groundwater has been carried out since 2018. Open data available from ukgeos.ac.uk provide a growing body of data releases (e.g. Bateson and Novellino 2019; Barkwith *et al.* 2020; Fordyce *et al.* 2020) and time-series monitoring data over the >15 years lifetime of the Glasgow Observatory. Geological models are also available (Arkley 2019; Burkin and Kearsey 2019).

Pre-drill geological and mining legacy datasets

Gathering and synthesis of geological, mining and hydrogeological legacy information prior to borehole drilling was critical in planning the borehole location, design and predicted target intervals.

Superficial and artificial deposits

The bedrock succession of eastern Glasgow is overlain by up to 40 m of glacial and post-glacial Quaternary deposits. The thick

accumulations infill a broadly NW–SE-trending channel of incised bedrock following the modern-day River Clyde (Browne and McMillan 1989; Forsyth *et al.* 1996). The succession commonly comprises variable thicknesses of Devensian glacial till overlain by glacio-fluvial sand and gravel. Widespread clay and silt of post-glacial raised marine deposits are overlain by sand, gravel, clay and silt of estuarine and fluvial deposits (Browne and McMillan 1989; Forsyth *et al.* 1996; Finlayson *et al.* 2010). A range of modelling has been undertaken to represent the 3D distribution of the superficial deposits at city scale (Monaghan *et al.* 2014; Kearsey *et al.* 2015, 2019b) with an updated pre-drill model presented by Arkley (2019).

Made, filled and landscaped ground is widespread from a variety of prior industrial land use, in some places 10–15 m thick. Former land use and made ground at Cuningar Loop includes a water works (northern end), colliery waste (southern end) and widespread up to c. 10 m thick cover of building demolition rubble added in the 1960s (Ramboll 2018a). At Dalmarnock, in the immediate vicinity of borehole GGC01, legacy boreholes indicated the made ground was expected to be around a metre thick. Several sites within 500 m of GGC01 are undergoing remediation of land contamination of the shallow subsurface (e.g. Farmer *et al.* 1999; Bewley and Sojka 2013) resulting from a multiplicity of former industrial land uses (Ramboll 2018b; Watson and Westaway 2020).

Bedrock

The Glasgow Observatory is located on the western side of the Central Coalfield of the Midland Valley of Scotland, an area formerly extensively mined for coal (Clough *et al.* 1926; Forsyth *et al.* 1996). The area is underlain by the c. 300 m thick Carboniferous Scottish Upper, Middle and Lower Coal Measures formations, comprising cyclical sedimentary sequences of sandstone, siltstone, mudstone, root-bearing palaeosol ('seatearth') and coal (further details have been given by Forsyth *et al.* 1996; Hall *et al.* 1998). Interpreted to have been deposited in dominantly fluvio-deltaic coastal plain and coal swamp environments, rare beds with marine fossils signify occasional marine incursions (Forsyth *et al.* 1996). Fossil beds such as the Cambuslang Musselband (or 'Marble') and centimetre-scale ironstone interbeds and nodules form subsidiary lithologies.

The Glasgow Upper, Glasgow Ell and Glasgow Main coal seams are commonly the thickest in the area, frequently between 1 and 1.5 m in thickness (Hall *et al.* 1998). Mine plans and records from the Farne Colliery that extended under Cuningar Loop summarize the Glasgow Upper as commonly 1.3 m thick, soft and 'wet' owing

Table 1. Summary of Glasgow Observatory boreholes

Site	Borehole number	Borehole type	Drilling method: superficial and bedrock sections	Total drilled depth from drill platform level (m)	Drilled diameter at total depth	Total casing depth from as-built datum (m)	Screen depth from as-built datum (m)	Screen type and internal casing diameter	Description of screened interval	ERT, fibre optics installed
1	GGA01	Mine water	Superficial and bedrock: rotary, reverse circulation	52.00	406 mm (16 inches)	51.11	44.81–48.41	4 mm slotted with pre-glued gravel pack, 248 mm ID	Overlying sandstone roof and Glasgow Upper mine working waste	Y
1	GGA02	Sensor testing	Superficial and bedrock: rotary, reverse circulation	94.16	406 mm (16 inches)	92.57	n.a.	248 mm ID	n.a. Grout-filled Glasgow Main target interval, screen inside casing up to 67.2 m	Y
1	GGA03r	Environmental monitoring	Superficial: rotary, direct circulation. Bedrock: rotary, reverse circulation	41.72	374 mm (14 ¾ inches)	40.81	37.00–39.81	3 mm slotted with pre-glued gravel pack, 146 mm ID	Sandstone bedrock, above Glasgow Upper mine working	N
2	GGA04	Mine water	Superficial and bedrock: rotary, reverse circulation	53.63	406 mm (16 inches)	53.00	47.40–51.00	4 mm slotted with pre-glued gravel pack, 248 mm ID	Overlying sandstone roof (fractured?) and Glasgow Upper mine working position, coal and mudstone	Y
2	GGA05	Mine water	Superficial: rotary, reverse and direct circulation. Bedrock: rotary, reverse circulation	88.50	406 mm (16 inches)	88.00	83.60–86.30	4 mm slotted no gravel pack, 248 mm ID	Overlying sandstone roof and Glasgow Main mine working, void to mudstone floor	Y
2	GGA06r	Environmental monitoring	Superficial: rotary, direct circulation	16.00	191 mm (7 ½ inches)	13.76	11.79–13.76	1 mm slotted with pre-glued gravel pack, 103.8 mm ID	Sand and gravel in superficial deposits	N
3	GGA07	Mine water	Superficial: duplex drilling, direct circulation. Bedrock: rotary, reverse circulation	56.90	406 mm (16 inches)	56.61	50.91–53.61	4 mm slotted pre-glued gravel pack, 248 mm ID	Overlying mudstone roof and Glasgow Upper mine working, coal pillar and void	Y
3	GGA08	Mine water	Superficial: rotary with reverse and direct circulation, and duplex drilling. Bedrock: rotary, reverse circulation	91.37	406 mm (16 inches)	87.95	85.08–87.70	4 mm slotted pre-glued gravel pack, 248 mm ID	Overlying sandstone–siltstone and Glasgow Main mine roadway void	Y
3	GGA09r	Environmental monitoring	Superficial: rotary, direct circulation	16.00	191 mm (7 ½ inches)	14.33	11.43–13.33	1 mm slotted with pre-glued gravel pack, 103.8 mm ID	Sand in superficial deposits	N
5	GGB04	Environmental monitoring	Superficial: rotary, direct circulation	16.00	191 mm (7 ½ inches)	12.99	10.09–11.99	1 mm slotted with pre-glued gravel pack, 103.8 mm ID	Sand and gravel in superficial deposits	N
5	GGB05	Environmental monitoring	Superficial: rotary with reverse and direct circulation, and duplex drilling. Bedrock: rotary, reverse circulation	46.00	374 mm (14 ¾ inches)	45.39	42.39–44.19	3 mm slotted with pre-glued gravel pack, 146 mm ID	Sandstone bedrock, above Glasgow Upper mine working	N
10	GGC01	Seismic monitoring	Geobore S coring	199.00	151 mm	198.30	n.a.	76.6 mm ID	n.a.	N

Grid references, drilled and datum heights are given in open data from ukgeos.ac.uk. n.a., not applicable; Y, yes; N, no. ©BGS, UKRI 2021.

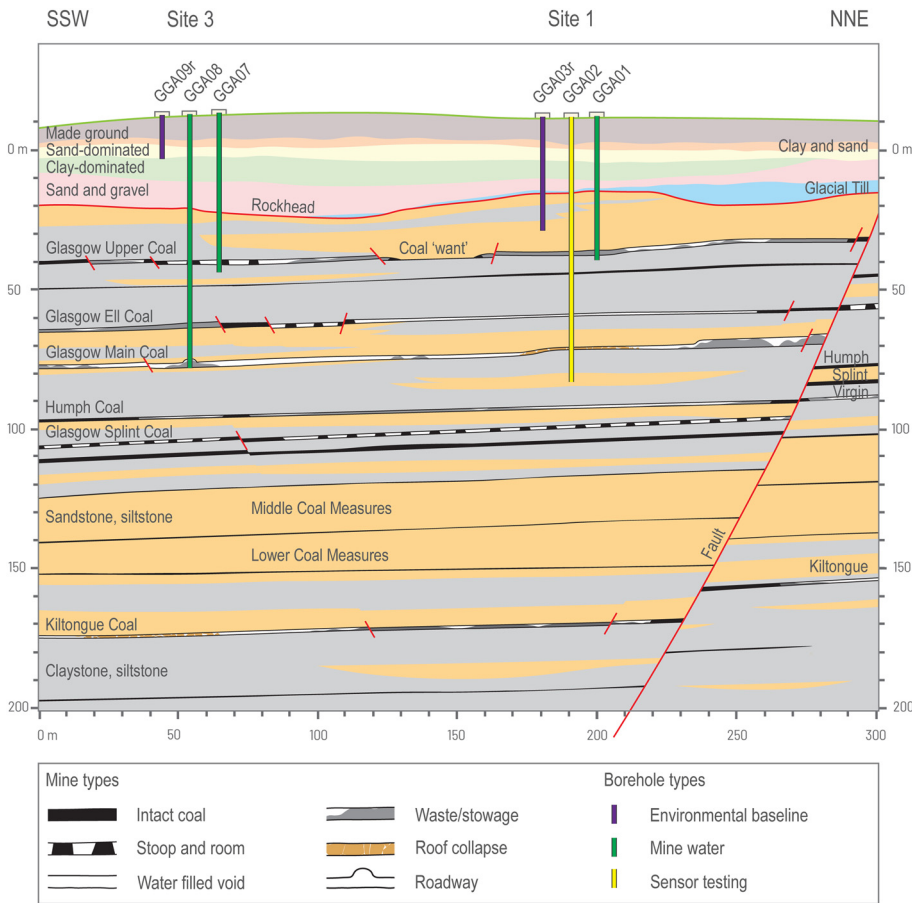


Fig. 4. Cross-section through sites 1 and 3 of the Glasgow Observatory interpreted from new and legacy borehole data, mine abandonment plan records and using 3D geological models. ©BGS, UKRI 2021.

to underlying impermeable claystone (Findlay *et al.* 2020). A type section of the Glasgow Ell coal is 1.09 m thick and the Glasgow Main is 1.35 m thick.

Within 5 km of the Glasgow Observatory location, the bedrock succession is cut by normal and oblique-slip faults on a variety of trends. The NW–SE-trending Dechmont Fault is a major, long-lived structure (Hall *et al.* 1998), and other WNW–ESE- to west–east-trending faults subdivide the succession into several kilometre-wide fault blocks (BGS 1992, 1993). Faults on similar trends to the larger structures, and north–south-trending faults, further cut the succession. Faulting dissects open folding within the strata. Situated north of an easterly trending syncline cored with the Upper Coal Measures, the rocks at Cuningar Loop dip around 1–3° to the SW (BGS 1992, 2008; Glasgow Ell mine abandonment plan ‘1 in 60’). The city-scale, faulted 3D geological model (Monaghan *et al.* 2014; Kearsley *et al.* 2019b) was updated to a pre-drill bedrock and mine model by Burkin and Kearsley (2019) during the definition and preliminary survey stages of the Glasgow Observatory.

Mining history and borehole planning

Mining information was gathered from multiple sources, including datasets openly available via The Coal Authority online viewer and via inspection of The Coal Authority archives for additional records (plan scans, pumping records, shaft records). The British Geological Survey (BGS) also holds archives of coal information (borehole records, coal properties information), and industrial heritage publications, which contain vital background information (Findlay *et al.* 2020). The knowledge of former miners, mine surveyors and engineers can inform how mines were left on abandonment and how they may have evolved since closure, exemplified at Heerlen (European Union 2008). Mining information for the Glasgow Observatory benefited from knowledge of a

former central Scotland, Coal Board mining surveyor employed by BGS (e.g. McLean 2018). Within the 5 by 4 km area surrounding the Glasgow Observatory, mine abandonment plans from 1810 to 1934 record the workings of eight coal seams from the Middle and Lower Coal Measures formations. Extents, depths, mining type, stone and coal roadways, etc. have been digitized by BGS from the mine abandonment plans and used in the geological and mine models of the area (Monaghan *et al.* 2014; Burkin and Kearsley 2019; Kearsley *et al.* 2019b).

Under the Cuningar Loop, seven coal seams were worked from the Farme Colliery between 1805 and 1928 (Findlay *et al.* 2020). A range of mining types are recorded on the mine abandonment plans including stoop (coal) and room (void) (pillar and stall) workings and ‘total extraction’ areas. The total extraction areas were marked as stoop and room workings on 1880s plans followed by removal of the pillars (pillar ‘robbing’) by the 1930s plans (Fig. 6), as opposed to longwall or shortwall mining methods. In total extraction areas without roof support, collapse to goaf (fractured rock) is expected to have occurred close to the time of removal of the pillar support (NCB 1975). Pillars in the Glasgow Upper coal seam have a pillar width/height ratio of around 3–10. The access shafts for the Farme Colliery were located to the SSW of the Glasgow Observatory boreholes, adjacent to what is now Downiebrae Road (Fig. 2). One of the mine shafts was grouted and plugged in 2013 (Ramboll 2018a, p. 36). Shaft ‘no. 4 pit’ is situated 220–300 m to the east of the Glasgow Observatory boreholes, close to the River Clyde.

Legacy borehole records from Cuningar Loop (e.g. BGS borehole numbers NS66SW BJ579, BJ583, BJ631) indicate the presence of voids, fractured rock with cavities, loose coal, loose or packed waste and stowage. Stowage is a term used for material used for backfill of mine workings during mining, as means of waste disposal and roof support. Stowage is likely to include a range of altered and stained clast types. ‘Waste’ recorded on legacy borehole



Fig. 5. Images of (a) drilling of the cored borehole GGC01 in 2018 and (b) installation of uPVC casing screen to mine water borehole with pre-glued gravel pack, electrical resistivity sensor cable (red sensors) and fibre optic cable. (a, b) BGS©UKRI 2020. (c) Research compound Site 1 at July 2020, background photograph courtesy BAM Nuttall.

records may include stowage, but it may also be collapsed roof material (goaf) or floor heave material. No pumping records have been located from the Farme Colliery or immediate vicinity. High and artesian water levels measured in boreholes penetrating the Glasgow Upper mine working are noted in some legacy data (e.g. NS66SW BJ579 in 1979), giving some clues about the hydraulic regime and notable for planning borehole drilling and construction.

Mine abandonment plans on several of the seams show that the Farme Colliery workings extended northwards under the River Clyde and were connected to a number of other collieries under the Clyde to the SE (e.g. Haugh Pit, Westhorn). In turn these collieries were connected to the east, south and possibly west (e.g. Stonelaw, Eastfield pits; an image of extents has been given by Monaghan *et al.* 2017, p. 20). Thus, depending on final abandonment and collapse state, substantial potential hydraulic interconnectivity of mine workings exists over a scale of kilometres.

The NW–SE-trending fault shown on the BGS 1:10 000 scale geological map (BGS 2008) at Cuningar Loop is derived from the abandonment plans through the seams (Fig. 6, top right corner of each plan image). Smaller faults with throws of c. 0.6–3 m on north, NW and WNW trends are common on the mine abandonment plans (Fig. 6), but it is not clear if, or how many, of these smaller faults are connected between seams. There are a number of stone roads

between seams (e.g. Glasgow Ell to Glasgow Main on the eastern side of Cuningar Loop), and former roadways within the coal workings are marked on a number of abandonment plans. The Glasgow Upper plan shows a number of ‘wants’ (i.e. sandstone channel washouts of the coal), most notably a NNE-trending ‘want’ between Glasgow Observatory sites 1 and 3 (Fig. 4). Mining records document a clean boundary to the sandstone want, with the coal thickness doubled in some places at the side of the want, and stone roads across the want recorded a coarse, pebbly base (Findlay *et al.* 2020, pp. 62–63).

Coal mining is not recorded in the mine abandonment plans for the site of the 199 m deep GGC01 borehole at Dalmarnock. However, based on plans to the east and shafts to the west, unrecorded mine workings were considered possible or probable, both on The Coal Authority online viewer and by BGS (Kearsey *et al.* 2019a). Possible mine workings were therefore considered when planning this borehole, which provides the cored and reference section for the Glasgow Observatory.

Implications for borehole planning

The pre-drill borehole planning for the Glasgow Observatory considered areas of both stoop and room and total extraction mine

workings. This contrasts with existing mine water energy schemes that focus on roadways and shafts (Verhoeven *et al.* 2014; Athresh *et al.* 2015; Burnside *et al.* 2016a, b; Banks *et al.* 2017) because of their probably very high hydrogeological yields for heat recovery. The rationale for the targets at the Glasgow Observatory included (1) lack of suitable land available over shafts and roadways and (2) the fact that different types of mine working are favourable for a research infrastructure to characterize potentially differing responses within these types of workings that are spatially extensive across the UK. For example, the heat dispersion characteristics of a fractured rock mass or mine waste are likely to be important for heat storage research.

Three of the mine water boreholes were planned to target the uppermost worked coal seam, of the Glasgow Upper Coal at *c.* 50 m. This is because for mine water heat resources, construction and operational costs are likely to be lower if the shallowest working is exploited, which may offset the gain of higher temperatures of deeper workings (e.g. Banks *et al.* (2017) noted the likely cost benefit of

raising a pump to shallower levels). Three boreholes were also planned to aim at the third shallowest mineworking, of the Glasgow Main Coal at *c.* 85 m. The rationale was to provide depth variability, complexity in potential pathways for abstraction–re-injection and thermal breakthrough research. A significant consideration was also that the Glasgow Main Coal has a sandstone roof, meaning that the mine working was thought to be more likely to be an open void or collapsed rock mass containing significant permeability. In contrast, the intervening Glasgow Ell Coal generally has a mudstone roof and was predicted to have more probably collapsed with resultant low permeability expected.

The error in georeferencing scans of old, cracked mine abandonment plans and the original surveying error was understood to be around 5–10 m in *XY*, larger than the scale of stoop and room workings recorded on the plan (contrast Fig. 6a and b). This led to significant uncertainty that any particular borehole position would hit an intended target. Nevertheless, for a target in stoop and room workings the borehole was positioned apparently in a ‘room’

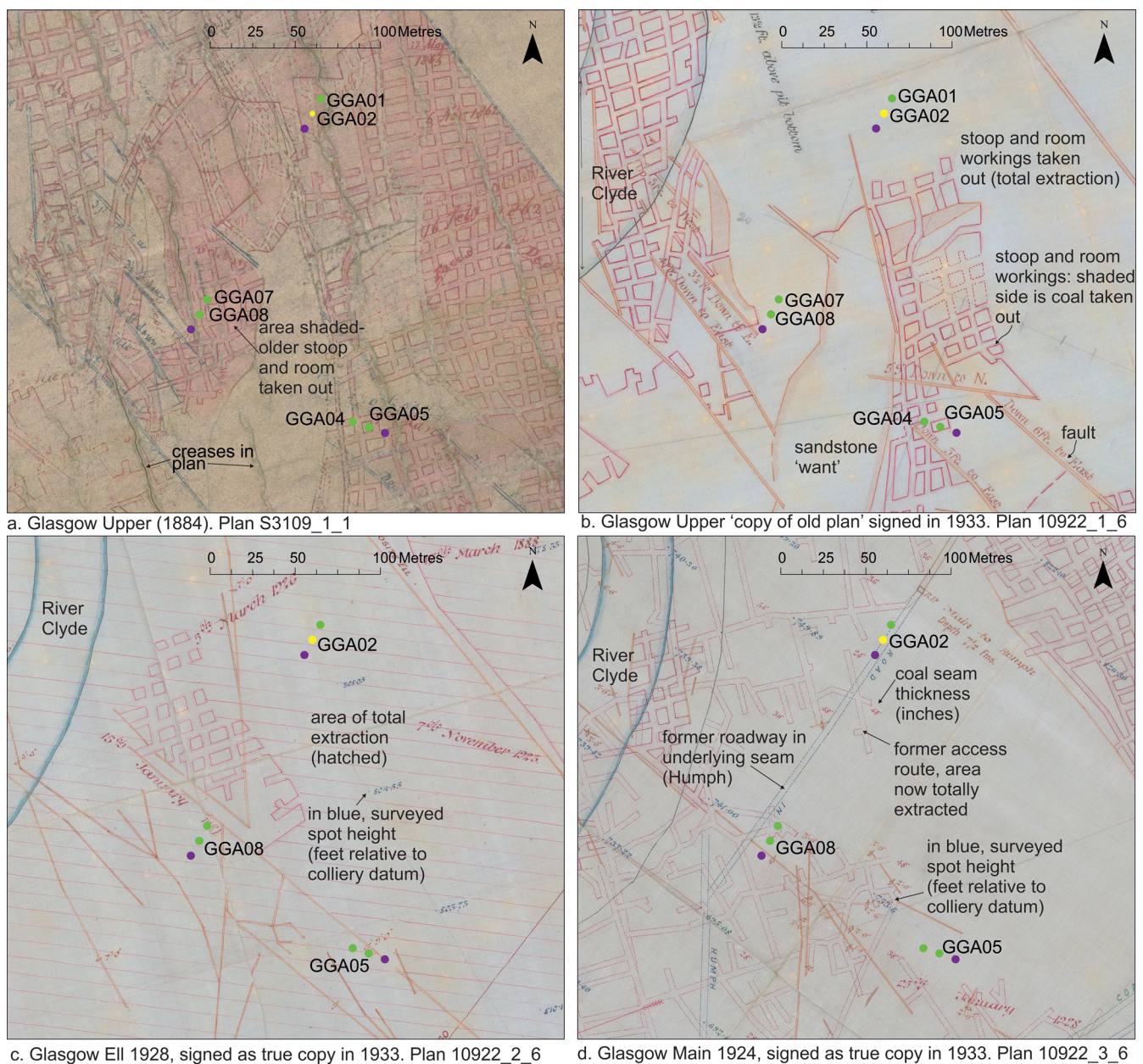


Fig. 6. Labeled images of georeferenced scans of Farme Colliery mine abandonment plans in the vicinity of the Glasgow Observatory boreholes. Boreholes penetrating the coal seam or mine working are labelled. Plan scans © The Coal Authority 2021. All rights reserved. Borehole locations and labels by the authors. Borehole colours as in Figure 2c.

(GGA04). For a borehole aiming at a deeper mine working, borehole positioning was in a 'stoop', to reduce drilling cost and risk (GGA05).

Environmental regulation and protection played a significant role in the design of the boreholes, along with scientific considerations. Agreed through the planning permission process and in discussion with the environmental regulator (Scottish Environment Protection Agency; SEPA), separate borehole casings were installed through the made ground, superficial deposits and bedrock sections of all the Glasgow Observatory boreholes at Cuningar Loop, with the annulus of the different casing sections grouted before the next section was drilled. This was to be done to prevent the mixing of groundwaters from different lithologies, which could occur if vertical flow paths were created during drilling. The boreholes were to be screened only across the target interval, with the annulus fully sealed with grout above the screen, so hydrogeological observations related only to the target interval. Finally, to preserve the *in situ* conditions for scientific research, and to minimize any environmental impact should one mine working contain water of much poorer quality, the Glasgow Upper and Glasgow Ell mine workings were planned to be sealed with a plug of grout before progressing to the Glasgow Main mine working target. This would be required until water chemistry samples taken from the mine workings indicated an interconnected mine water body.

Results: borehole drilling and construction

Comprehensive descriptions of the borehole drilling, casing and grouting, the as-built design and the lithology and stratigraphy of each Glasgow Observatory borehole have been given by [Kearsey et al. \(2019a\)](#), [Barron et al. \(2020a, b\)](#), [Elsome et al. \(2020\)](#), [Monaghan et al. \(2020a, b, c\)](#), [Shorter et al. \(2020a, b\)](#), [Starcher et al. \(2020a, b\)](#) and [Walker-Verkuil et al. \(2020a, b\)](#). Some key aspects are summarized here.

All boreholes at Cuningar Loop had the same initial drilling diameter of 880 mm (34 $\frac{3}{4}$ inches) for the made ground section, which was drilled using a piling rig with auger. The superficial deposits and bedrock sections had progressively smaller drilling diameters, and the drilled diameter at total depth varied between environmental baseline monitoring and mine water boreholes (Table 1). The open-hole superficial and bedrock sections at Cuningar Loop used reverse circulation, rotary drilling as standard for good sample recovery and to prevent loss of flush into the mine workings. Direct circulation with rotary drilling and duplex drilling (drilling while casing) was used when difficulties were encountered, either with clogging of the bit in claystones, or in an unstable hole in sand and gravel within the superficial deposits (Table 1). The drilling rig used a collared drill string to run behind the bit, giving a stiffer bottom hole assembly and helping to produce straight and vertical boreholes. Verticality in the mine water boreholes was surveyed using a cased hole wireline inclination tool. All the mine water boreholes at Cuningar Loop were within 2° of vertical; the base of the 199 m deep borehole GGC01 was 1.84 m from the vertical.

Steel was used for the made ground and superficial deposits casings and uPVC Boode casing was used for the screened sections and bedrock sections. The annulus of each casing section was grouted using either Ordinary Portland Cement (OPC) or Tarmac Pozament SP/F6 mix (made ground and superficial casings) and SP/F6 or bentonite cement pellets (bedrock section) above a rubber annular seal topped with a bentonite plug (mine water boreholes) or a simple bentonite plug (superficial and bedrock boreholes). A pre-glued gravel pack was used in all boreholes except those in a mine working void, to prevent ingress of fines and rock pieces or other material that could clog the slotted screen. The gravel size was chosen to correspond to the screen slot size. After problems were encountered with borehole GGA02 ([Monaghan et al. 2020c](#)), an

optical camera and caliper wireline log were run in the open hole mine water boreholes to determine the character of the mine working, associated fracturing and placement of the annular seal. This working information was not part of the planned data collection. The risk of open hole instability, and time and cost constraints, meant that a more comprehensive wireline log suite was not possible.

Here we provide a synthesis integrating the 12 new boreholes with legacy data.

Results: post-drill lithology and stratigraphy

Superficial deposits

The thickness of made ground in the 11 Cuningar Loop boreholes varied from 7.5 to 9 m, and was 0.6 m in GGC01 at Dalmarnock (Fig. 7). The composition at Cuningar Loop included brickwork, concrete sandstone cobbles and boulders, ashy sand, gravel, wood, clinker, glass, slate and plastic. This is consistent with the area being used for landfill following building demolition. Natural superficial deposits show thickness variability across Cuningar Loop from 26 to 40 m, although the precise position of the top of bedrock over weathered sandstone bedrock was difficult to ascertain in some boreholes (e.g. GGB05).

In the superficial deposits section, the returns records from GGA03r and GGA07 reflect a change in drilling method from reverse circulation to direct flush. This had a significant impact on the returns such that these records are not utilized in this synthesis (Fig. 7). Below the made ground, the natural succession comprised a sand and clay unit and a sand and gravel unit interpreted as the Gourrock Sand Member. Three environmental baseline boreholes were screened at this interval. This unit was underlain by clay and silt of the Paisley Clay Member, up to 12 m thick. A c. 1 m thick sand and gravel interbed is notable in boreholes in the south and east of Cuningar Loop (e.g. GGB05).

Legacy boreholes record variable thicknesses, from 0.7 m to over 12 m, of diamicton, boulder clay or glacial till at the base of the superficial deposits in the southern half of Cuningar Loop (e.g. BGS borehole numbers NS66SW SE17585 C3 and C5). At the northern end of the Loop, glacial till is not recorded, with up to c. 18 m of sand and gravel above the top of bedrock (e.g. NS66SW BJ2463) interpreted as the Broomhouse Sand and Gravel Formation ([Arkley 2019](#)). The Glasgow Observatory boreholes encountered more sand and gravel and less glacial till than was predicted; for example, around 1 m of till interpreted in GGA01, compared with over 6 m in NS66SW BJ579 15 m away. Boreholes GGA04 and GGA05 located 10 m apart returned significantly different successions below the Paisley Clay Member. GGA04 returns were of nearly 12 m thick gravel and sand, whereas GGA05 encountered around 4 m of sand and gravel overlying 7 m of clay, silt, sand and gravel interpreted as glacial till. Taken together, the legacy and new boreholes suggest a channelized sand and gravel deposit, interpreted as a southerly extension of the Broomhouse Sand and Gravel Formation. The sand and gravel caused some unexpected drilling problems ([Starcher et al. 2021](#)).

A similar succession of glacial till, fluvio-glacial sand and gravel, raised estuarine clay, and alluvial sand of 30.5 m thickness was observed in borehole GCC01 at Dalmarnock ([Kearsey et al. 2019a](#)). More widely, the superficial deposits succession across the Glasgow Observatory is typical of the Quaternary succession in the River Clyde valley.

Bedrock

The bedrock sections of the Glasgow Observatory boreholes are typical of the Scottish Coal Measures Group, comprising

interbedded claystone, siltstone and sandstone with coal, palaeosols with roots, ironstone beds and nodules, and fossil beds (Kearsey *et al.* 2019a; Barron *et al.* 2020a, b; Monaghan *et al.* 2020b, c; Starcher *et al.* 2020a, b; Figs 7 and 8). Variability between boreholes is notable; for example, the interval above the Glasgow Upper coal is commonly sandstone-dominated in legacy boreholes, GGA01 and GGA02. However, in GGA07 and GGA08 the interval was claystone–siltstone dominated (Fig. 7), possibly representing overbank deposits to fluvial channels or interdistributary bays. The interval between the Glasgow Upper and Glasgow Ell coals is typically mudstone dominated, with a heterolithic interval including the Cambuslang Musselband between the Glasgow Ell and Glasgow Main coals (Figs 7 and 8). The thickness of the coals shows some variability; for example, the Glasgow Upper coal as recorded varied from 1.14 m in GGA04 to 1.7 m in GGA07, consistent with mining records and legacy boreholes.

Results: post-drill mine workings

Considerations for drilling practice

Recognizing mine workings when drilling and characterizing them accordingly is evidently critical to realizing a mine water resource. Open hole, reverse circulation rotary borehole drilling at the Glasgow Observatory utilized a range of features to identify mine workings (Table 2), in conjunction with an experienced drilling contractor. The characteristic features are similar to those listed by Dennehy *et al.* (2019, p. 317) for recording during open hole drilling of abandoned mine workings, although that work was not published at the time of drilling. The mine workings predicted were

most frequently identified by change in rate of penetration, character of rock chip returns and smell of H₂S (Tables 2 and 3) or when coals were returned. Nevertheless, one instance of a packed waste was identified from an open-hole borehole optical camera log (GGA05, Glasgow Ell) and one mine working was not identified during drilling (GGA02 Glasgow Main). The large drill bit needed for the 406 mm wide diameter boreholes may have impeded recognition of tightly packed or fully collapsed workings (Starcher *et al.* 2021). Lessons learnt during construction of the first mine water boreholes proved the benefit using a borehole camera and caliper log on the open hole prior to casing, to categorize the mine water reservoir, place the screened section and identify a smooth rock wall for placing of the rubber annular seal (Starcher *et al.* 2021).

Sealing of the Glasgow Upper and Glasgow Ell mine workings in borehole GGA02 *en route* to the Glasgow Main target took time (Monaghan *et al.* 2020c). The mine water chemistry results from the Glasgow Upper working in GGA02 and Glasgow Main working in GGA05 were critical in proving similar groundwater chemistries. This indicated an interconnected mine water body and meant during-construction sealing of the Glasgow Upper and Ell workings in later boreholes (GGA08) was not required for environmental protection and scientific reasons, saving time and cost.

Variability encountered in target mine working intervals

The Glasgow Observatory boreholes penetrated mine waste, open voids, fractured rock and intact coal in areas indicated on the abandonment plans as total extraction or stoop and room workings (Table 3, Figs 7–9; see details given by Barron *et al.* 2020a, b; Monaghan *et al.* 2020a, b, c; Starcher *et al.* 2020a, b). The variable

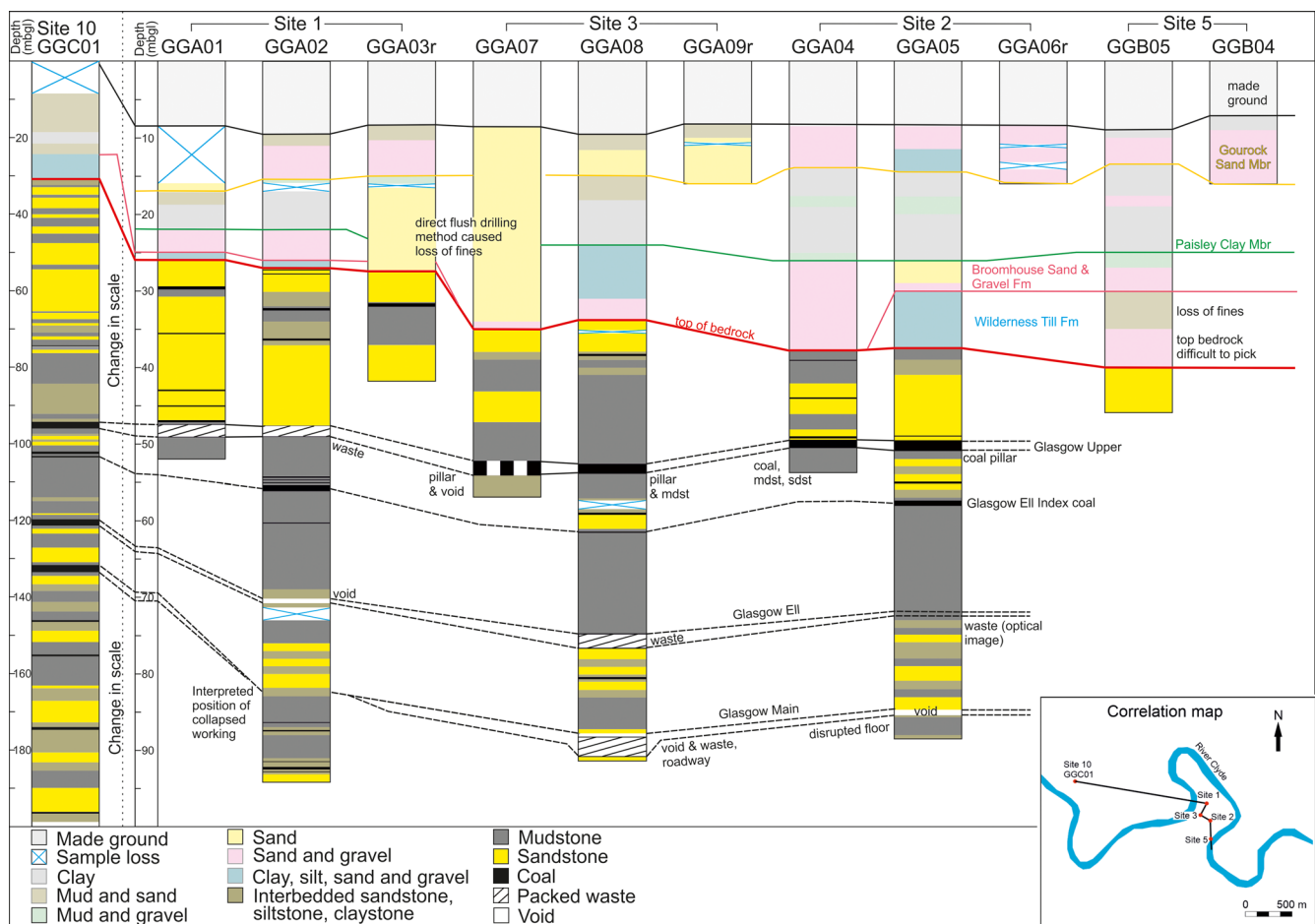


Fig. 7. Lithostratigraphical correlation panel of the Glasgow Observatory boreholes. Cuningar Loop boreholes summarized and interpreted from open hole rock chips. GGC01 sedimentology core log at a different scale. ©BGS, UKRI 2021.

character of the mine workings was not easily predicted from the mine abandonment plan. In contrast, the depths of the mine workings were well predicted by the mine abandonment plan spot heights (Table 3). The pre-drill borehole predictions proved a good indicator for the depth of the Glasgow Upper and Glasgow Main workings. The first Glasgow Ell mineworking to be penetrated (GGA02) was around 6 m shallower than predicted from the semi-regional model, but compatible with a mine spot height 30 m away, so updated predictions were created for subsequent boreholes (Table 3). The knowledge gained on drilling into mine workings varied by seam and location, as described in the following subsections.

Glasgow Upper. An area shown on the Glasgow Upper mine abandonment plan as ‘total extraction’ contains some intact coal pillars as well as voids and waste (GGA07, GGA08; Figs 7–9). Around 120 m away in a ‘total extraction’ area, a mine waste (stowage) was encountered (GGA01, GGA02). The areas of stoop and room workings on the abandonment plan encountered both coal and an interpreted fractured coal pillar (GGA05, GGA04 respectively) confirming that this coal had not been ‘robbed’. The main learnings from the six boreholes encountering the Glasgow Upper were that there was more coal remaining as pillars than expected. Fracturing or disturbance above and below coal pillars is described below and in Table 3.

Glasgow Ell. The Glasgow Ell coal seam is documented as 1.1 m thick on the abandonment plan, yet the boreholes penetrated one open void (GGA02) and two packed wastes (GGA05, GGA08) all around 0.7 m thick, indicating collapse of the mine working from the original worked thickness. All boreholes were in zones marked as total extraction on the Glasgow Ell abandonment plan, and collapse may be prevalent owing to weakness of the mudstone-dominated roof. On the borehole camera log the wastes appear as a tightly packed breccia with mudstone matrix, with a migrated void 2 m above in GGA08 (Fig. 9).

Glasgow Main. The abandonment plans indicate total extraction of the Glasgow Main coal. The mine workings were open voids

with a sandstone roof and underlying wood or waste (GGA08) or disturbed zone (GGA05; Tables 2 and 3; Fig. 9). There were a number of former roadways marked on the abandonment plans within the total extraction area. The 3 m thick void–waste–wood returns and CCTV data from GGA08 indicated that a roadway had been penetrated with wooden supports still in place. In the third Glasgow Main borehole (GGA02), the mine working was not recognized during drilling and is interpreted as a clean collapse (Monaghan *et al.* 2020c).

The cored, reference borehole GGC01 at Dalmarnock returned intact coals, proving that there were not unrecorded mine workings within an area judged pre-drilling as having possible or probable workings (Kearsey *et al.* 2019a).

Mining-induced fracturing and disturbance

Outcrops and opencast coal sites exposures highlight the complexity of natural faulting and fracturing in heterolithic Carboniferous successions (e.g. Andrews *et al.* 2020b), which strongly influences groundwater flow (O Dochartaigh *et al.* 2015). Mine plans themselves form a valuable source of fault information (Rippon 1984; Walsh and Watterson 1988; Huggins *et al.* 1995; Monaghan 2017). In the case of the Cuningar Loop, mine plans record faults with *c.* 0.6–3 m throw on north, NW and WNW trends that were mined across. Natural discontinuities have also been documented in the cored Glasgow Observatory borehole GGC01, with numerous thin veins that exploited the coal cleat system and sparse discontinuities in other lithologies including mineralized and non-mineralized joints, slip surfaces and faults (Kearsey *et al.* 2019a). A subset of the discontinuities were unsealed and potentially transmissive, commonly with brittle fracturing in sandstone and slip surfaces in mudstone (Kearsey *et al.* 2019a).

Mining causes an additional complex series of anthropogenically generated voids, fractures and collapses. The character and migration of fractures and collapses in relation to subsidence have been extensively covered in the mining literature, with control by

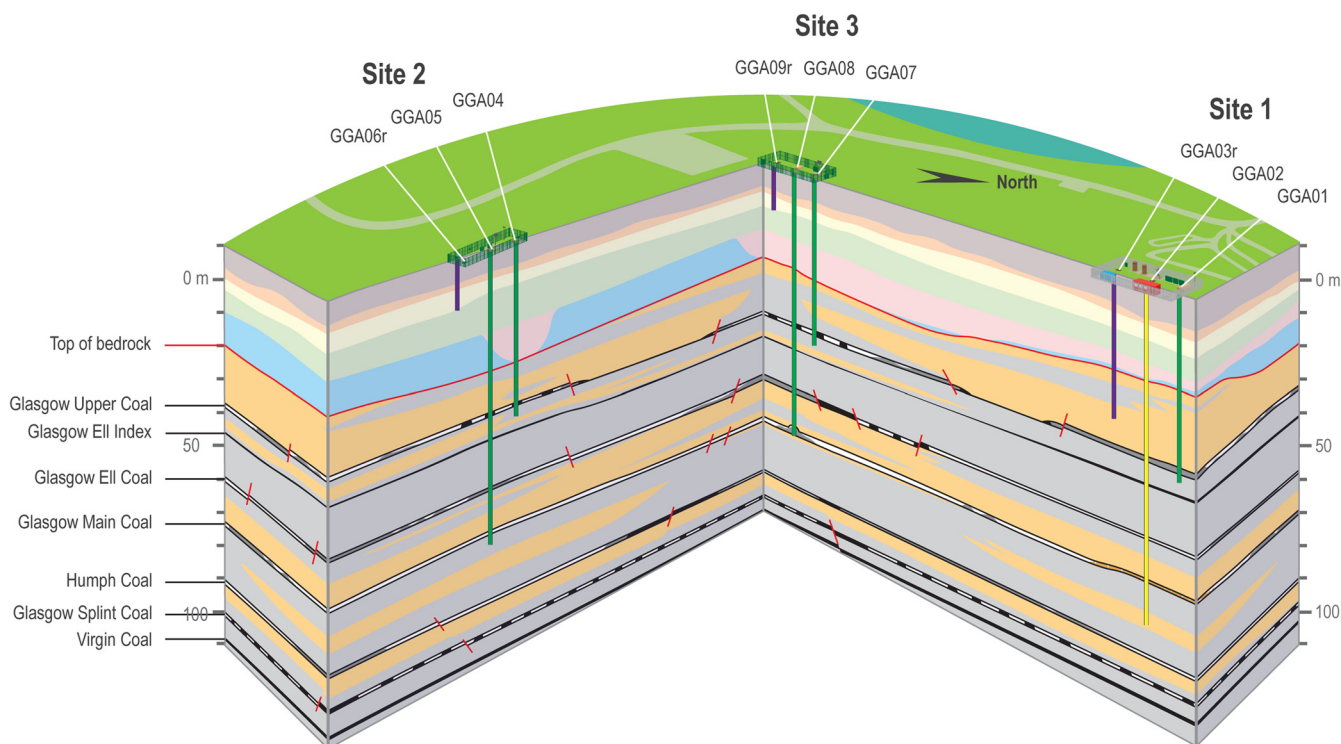


Fig. 8. Interpretative 3D block diagram to illustrate borehole geometry, and proved and interpreted mine working variability indicated by abandonment plans. No vertical exaggeration (colours and fills as in Fig. 4). ©BGS, UKRI 2021.

Table 2. Features used to recognize mine workings during open hole rotary drilling of the Glasgow Observatory boreholes at Cuningar Loop in 2019; ©BGS, UKRI 2021

Feature	Caused by:	Recognized during Glasgow Observatory borehole drilling
Clean drop of core barrel	Open mine working, void	GGA02, Glasgow Ell GGA05, Glasgow Main
Increased rate of penetration, increased cuttings returns	Easier progress through mine 'waste' (stowage or backfill, collapsed or fractured rock)	GGA01, Glasgow Upper GGA02, Glasgow Upper GGA08, Glasgow Upper GGA08, Glasgow Ell
Wobbling or 'torquing-up' of drill bit Smell of H ₂ S (rotten eggs) and/or gas monitor alarm	Sometimes indicates fractured rock mass Mine gas or mine water	GGA05 above Glasgow Main Smell (alarm not activated): GGA01, Glasgow Upper GGA02, Glasgow Ell GGA05, Glasgow Ell (faint) GGA05, Glasgow Main GGA08, Glasgow Upper GGA08, Glasgow Main
Loss of fluid flush	If using direct circulation, fluid flush would be lost into the mine working	Reverse circulation was used to avoid loss of flush
Returns of iron- and sulphur-stained coal, mudstone, siltstone, sandstone (mixed lithologies)	Returns of mine waste, may be loose to densely packed. Mixed, stained lithologies interpreted as stowage	GGA01, Glasgow Upper GGA02, Glasgow Upper GGA08, Glasgow Ell GGA08, Glasgow Main
Returns of wood, metal, rubber	Roof support, pit prop, roadway, trackway and similar (first confirm nothing has been dropped down the borehole)	GGA02, Glasgow Upper GGA08, Glasgow Main
Returns of stained, altered coal	Edge of coal pillar or collapsed, fractured pillar	GGA07, Glasgow Upper GGA08, Glasgow Upper
Excess water at shakers Substantial kick(s) in caliper log	Fractured rock above mine working Void, waste or fractured rock	GGA08, above Glasgow Upper GGA04, above Glasgow Upper GGA05, all 3 workings GGA07, Glasgow Upper GGA08, all 3 workings
Voids, wastes, fractures, disturbed strata visible on optical camera		GGA05, all 3 workings GGA07, Glasgow Upper GGA08, all 3 workings

style of mining, rock lithologies and thicknesses, natural fault or fracture system, stress fields, etc. (e.g. NCB 1975; Healy and Head 1984; a summary has been given by Mason *et al.* 2019). The effects on groundwater flow and flow properties (Younger and Adams 1999), and any evolution through time for legacy mines is less extensively documented, particularly the implications for mine water heat abstraction and heat storage (Andrews *et al.* 2020a). An initial summary of the observed fractures and disruption observed in the Cuningar Loop mine water boreholes from adjacent to the mine workings is therefore important for future hydrogeological testing, and conceptual and numerical modelling of mine water resources.

Borehole camera and open hole caliper logs from five of the boreholes indicate that mining-induced subvertical fractures and disrupted zones are restricted to within 1–2 m above and below the mine workings (Table 3, Fig. 9). Fracturing and disturbance above mine workings is of variable character. In GGA05, where the borehole is interpreted to have drilled through an intact coal pillar, the borehole camera log appears to show open fractures along horizontal bedding planes for around 6 m above the Glasgow Upper coal (Table 3, Fig. 9). In GGA04 and GGA08, where the borehole has drilled through what is interpreted as a fractured or disrupted pillar and part void or waste, the roof is disrupted for around 1–1.5 m above the Glasgow Upper mine working. Fracturing in the mudstone roof of the Glasgow Upper pillar or void is not easily discerned in borehole GGA07.

Where a packed waste was encountered in the mine working, fracturing and void migration are observed for around 2 m above the roof strata of the Glasgow Ell mine working (GGA05, GGA08, Table 3, Fig. 9). Finally, where a clear void is encountered in the Glasgow Main mine working, the sandstone roof strata appear undisturbed in GGA05 and with some fracturing for 1–2 m above the sandstone roof in GGA08 (Table 3, Fig. 9).

The mine workings' floor zone shows 1–2 m of fracturing beneath the Glasgow Upper coal pillar and Glasgow Ell packed waste in borehole GGA05 (Fig. 9). The floor of the Glasgow Upper mine working (a grey claystone) appears visibly disrupted beneath an intact pillar (GGA05) or part pillar or waste (GGA08), typically with a caliper kick of around 0.2 m below the floor (GGA04, GGA05, GGA08). Minor losses during annulus grouting of this interval were observed in GGA05. This could be a result of floor heave and lift of this weak lithology through swelling upon flooding of the mine and/or induced strains caused by 'pillar punching', both being common phenomena recognized in mine workings (Healy and Head 1984; Wuest 1992; Mason *et al.* 2019, p. 129; Mo *et al.* 2020). The floor of the Glasgow Main mine working in borehole GGA05 exhibits 1.7 m of broken rock and a basal caved zone (Fig. 9) that was not detected or interpreted as mine waste from rock chip returns of siltstone and very fine sandstone. This disrupted section is tentatively interpreted to be have been affected by floor lift or heave.

Table 3. Predicted and observed depth and lithology or type of the mine water boreholes, listed in order of drilling

Borehole; coal (in order of drilling)	Predicted drill depth; Glasgow Upper and Main target workings with error margin (m)	Observed drilled depths of mine working (top–base) from drill platform (m)	Predicted mine working type from mine plans	Observed mine working type	Observed mining-related collapse and fracture features above or below working
GGA02; GU	45 ± 4	47.80–48.95	Area of total extraction following earlier irregular-shaped worked areas and roadways	Loose to moderately packed waste	No data
GGA02; GE	77	70.16–70.76	Total extraction	Open void	No data
GGA02; GMA	83 ± 2	Not recognized	Total extraction	Not recognized; interpreted as cleanly collapsed working	No data
GGA01; GU	45 ± 4	47.60–48.86	Area of total extraction following earlier irregular-shaped worked areas and roadways	Loosely packed waste; mixed lithologies	No data
GGA05; GU*	51 ± 2	49.46–51.00	Stoop and room (coal stoop or pillar)	Coal pillar	Horizontal bedding planes for <i>c.</i> 6 m above appear as open fractures. About 0.2 m disruption below pillar in claystone floor (caliper kick). Minor loss during annulus grouting. Fracture for <i>c.</i> 2 m beneath floor lift or heave or pillar punching?
GGA05; GE*	72 [†]	71.90–72.6	Total extraction	Tightly packed waste <i>c.</i> 0.7 m, not recognized during drilling, seen on optical camera and caliper log	Fractures 1–2 m above and below the mine working from optical camera
GGA05; GMA*	86 ± 2	84.66–85.36	Total extraction	Open, water-filled void. Underlying floor lift zone	Disrupted floor zone on optical camera and caliper data. Siltstone–fine sandstone rock chip returns (not waste), interpreted as 1.7 m of floor lift
GGA04; GU	51 ± 2	49.46–50.60	Stoop and room (room or void)	Fractured roof and coal; edge or collapsed pillar?	Caliper log and rock chip returns indicate <i>c.</i> 1.5 m fractured sandstone in roof of coal. Also caliper kick in mudstone below coal
GGA08; GU*	51 ± 2	52.50–53.70	Total extraction	Intact coal and waste; hit edge of a pillar	Optical camera and caliper show disrupted mudstone roof <i>c.</i> 1 m above. Disrupted floor <i>c.</i> 0.2 m below
GGA08; GE*	Between 72 and 81 [†]	74.70–76.50	Total extraction	Densely packed waste	Optical camera and caliper show fracture and migrated void 2 m above mine working. Intact rock below
GGA08; GMA*	88 ± 2	87.70–90.70	Total extraction and former roadway	Open void to collapsed material, wood, waste; the thickness indicates a mine roadway	Fractures for around 1.2 m above roof of mine working on optical camera
GGA07; GU*	51 ± 2	52.2–53.9	Total extraction	Coal pillar and void on optical camera and caliper kick	Fracturing not discernible in mudstone roof

*Optical camera data are available and constrain the interpretation. GGA04 interpretation includes open hole caliper data but not optical camera data.

[†]Adjusted from published pre-drill predictions during the drilling phase based on the depth of GGA02.

GU, Glasgow Upper; GE, Glasgow Ell; GMA, Glasgow Main. ©BGS, UKRI 2021.

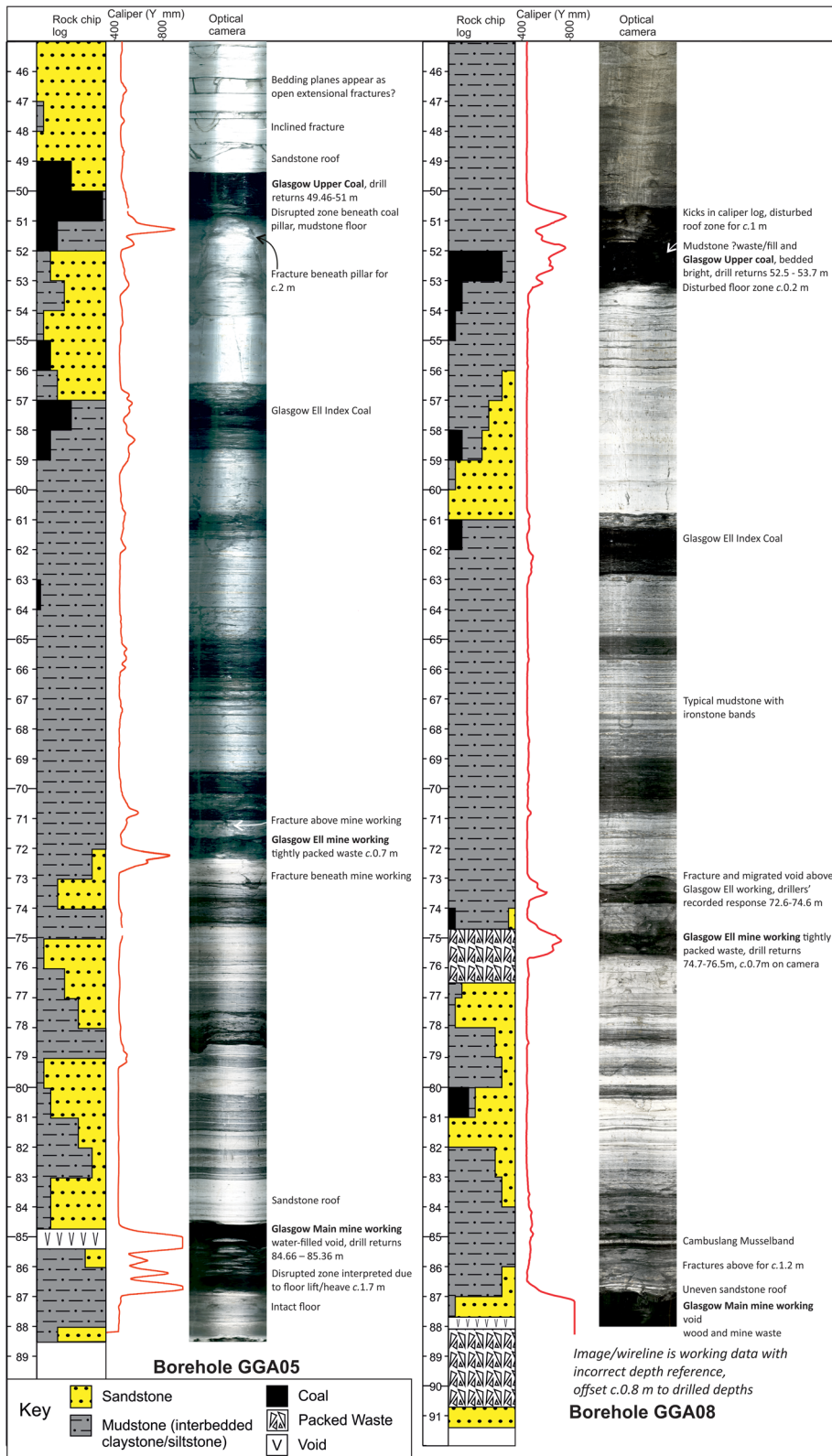


Fig. 9. Rock chip log, caliper log and camera optical log images from the Glasgow Upper to Glasgow Main coal seam and mine workings section of boreholes GGA05 and GGA08. ©BGS, UKRI 2021.

To gain a first understanding of whether this qualitative description of mining-induced fracturing and disturbance in the Glasgow boreholes is representative of the rock mass as a whole, comparisons can be made with the literature. During active mining in the UK, an observation-based ‘ten times the height of the mine working rule of thumb’ was used to estimate acceptable bedrock cover thicknesses against migration of mine working voids or collapses to surface (Mason *et al.* 2019). However, the rule of thumb was varied between 2–7 times the worked thickness and greater

than 10 times, depending on type of roof strata, residual voidage and several other factors (Mason *et al.* 2019). Andrews (2019) documented the majority of deformation 5–15 m above collapsed c. 2 m thick pillar and stall workings exposed in an opencast site, with some faulting interpreted to around 50 m above the collapsed workings. Well-established numerical methods estimating collapse mechanisms, fracturing and subsidence owing to mining also exist (NCB 1975; summaries have been given by Healy and Head 1984; Mason *et al.* 2019), highlighting the variability in mining-induced

disturbance with strong control by lithology, mining method, number of seams mined, etc. In the Glasgow Observatory boreholes, the Glasgow Upper mine working varies from 1.15 to 1.7 m thick, so the ‘ten times rule of thumb’ is substantially larger than the 1–2 m, possibly up to 6 m, zone of disturbance observed. However, the Glasgow Upper mine workings have not collapsed where drilled, with intact pillars and packed waste or stowage. The Glasgow Ell mine working has partially collapsed onto a packed waste with fracturing and void migration for 2 m in GGA08, smaller than the ‘rule of thumb’ would predict. Further evaluation is needed to understand whether the Glasgow Observatory boreholes probably typify the mining-induced disturbance around worked seams at Cuningar Loop based on the particular rock characteristics, or whether the borehole observed disturbance is not representative of the wider rock mass.

In summary, the borehole observations from the Glasgow Observatory indicate that there is commonly, but not always, a 1–2 m volume of rock mass above and below mine workings with properties significantly affected by fracturing or deformation. Possible implications for hydraulic properties include inclusion of fracture-dominated flow adjacent to pipe flow (voids) or porous media flow (loosely packed wastes or floor heave), adding to the overall hydraulic conductivity and storativity of the anthropogenically altered rock mass. Increased hydraulic conductivity and storativity may in turn have implications for geomechanical, geochemical and geomicrobiological properties and evolution that have yet to be fully understood. For heat storage applications, the fracturing and deformation zones adjacent to the mine working may form discontinuities useful for heat dispersion and heat recovery, adjacent to the high-permeability mine working. Additional work is needed to better characterize the rock mass at field scale and to understand the processes that may enhance or reduce hydraulic conductivity since mine closure.

Hydrogeological borehole testing

Having constructed the Glasgow Observatory boreholes, initial testing of the hydrogeological yields and responses was carried out to appraise future research uses and permanent heat abstraction and re-injection infrastructure. The outcomes were critical as, for a mine water borehole, the yields and aquifer properties amount to success or failure for the resource.

The initial resource appraisal began during the construction stages. First, it was determined that the boreholes all encountered flooded mine workings and that mine water levels were commonly 1–3 m below ground surface (Barron *et al.* 2020a, b; Monaghan *et al.* 2020b, c; Starcher *et al.* 2020a, b). Second, initial indications of high yields were gleaned from borehole flushing and cleaning during construction; for example, 38 m³ was air-lifted from borehole GGA05 Glasgow Main mine working in 45 min (Barron *et al.* 2020b), proving a large yield before more structured test pumping.

Test pumping was undertaken after all borehole construction had been completed to ensure that the groundwater regime was not affected by those activities (24 days minimum separation). It comprised 5 h step and constant rate pumping tests on 10 boreholes, including groundwater pressure, temperature and conductivity monitoring of surrounding mine water and environmental baseline boreholes. Full results have been reported by Shorter *et al.* (2021). For the mine water boreholes, the majority of the 5 h step tests pumped at *c.* 5/10/15/20/25 l s⁻¹ and the majority of the 5 h constant rate tests were pumped at a maximum of 20 l s⁻¹. The length and rate of test pumping was constrained by water disposal. Geochemical analysis of mine water during borehole construction proved the groundwater to be suitable for disposal to the River Clyde and a SEPA discharge licence was granted for

volumes of up to 369 m³ per day and maximum rate of 20 l s⁻¹ after passing through tanks to allow settling of suspended solids.

Monitoring of water-level recovery after the test pumping and time-series data from the downhole hydrogeological data loggers provide more information on the initial resource characterization and a basic understanding of the connectivity within the mine water and groundwater system (full results have been given by Shorter *et al.* 2021). In the environmental baseline boreholes, initial monitoring has recorded variable water levels and variable yields from test pumping. In four of the mine water boreholes (GGA01, GGA05, GGA07, GGA08) flow rates of 20 l s⁻¹ with limited drawdown between 1.49 and 4.24 m and temperatures around 12°C were achieved during 5 h constant rate test pumping. Good connectivity within each of the Glasgow Upper and Glasgow Main mine workings, and a response in the Glasgow Upper with pumping of the Glasgow Main mine working was observed from water-level responses (Shorter *et al.* 2021). This is promising for discerning responses during future research at the Glasgow Observatory on experimental timescales, with more complex linkages between different depth mine workings being useful for research on thermal breakthrough and tracers.

Discussion

Mine water reservoir classification

Borehole drilling at the Glasgow Observatory encountered a range of flooded mine workings from open voids, loose and packed waste to fractured rock mass, which exert influence on the hydrogeological (hydraulic) properties and therefore the recoverable mine water resource. Here we propose reservoir classifications (Fig. 10a–h).

Open voids penetrated within total extraction areas of the Glasgow Main mine working (GGA05, GGA08; Fig. 10e) and a void adjacent to a coal pillar in the Glasgow Upper mine working (GGA07) proved high yields on initial test pumping. The ‘open void’ reservoir classification is similar to shafts and roadways that are commonly the target for mine water schemes (Verhoeven *et al.* 2014; Athresh *et al.* 2015; Burnside *et al.* 2016a, b; Banks *et al.* 2017) and would appear to be the most promising for an economic mine water heat abstraction resource. Longer duration pumping is required to understand the local–regional connectivity and sustainability of the ‘open void’ reservoir at the Glasgow Observatory.

High yields were obtained from test pumping of a mining waste (stowage) reservoir classification (Fig. 10g) in GGA01 and with similar indications in GGA02 from an initial airlift during construction. These boreholes penetrate a total extraction area on the mine abandonment plan, highlighting that, depending on recharge and connectivity, there is resource potential in spatially extensive areas, away from shafts and roadways. The properties of mining waste, stowage, collapsed roof material (goaf), or floor lift or heave material are likely to be very variable depending on such factors as lithology, groundwater flow, collapse and sedimentation processes since mining ended (Fig. 10f–h), with more tightly packed wastes having smaller yields, perhaps offering resource potential for heat storage.

The fractured rock mass around or inside deformed coal pillars, or where there has been clean collapse of a mine working, or surrounding the mine working could also be considered types of mine water reservoir (Fig. 10a and d). Borehole GGA04 is interpreted with a fractured sandstone roof and possibly a partially collapsed pillar. Initial 5 h test pumping resulted in a yield of 15 l s⁻¹ but with greater 20.97 m drawdown than in the other mine water boreholes (Starcher *et al.* 2020a). Boreholes penetrating this type of fractured rock mine water reservoir may form a resource for small-scale schemes, or may have potential for heat storage as they

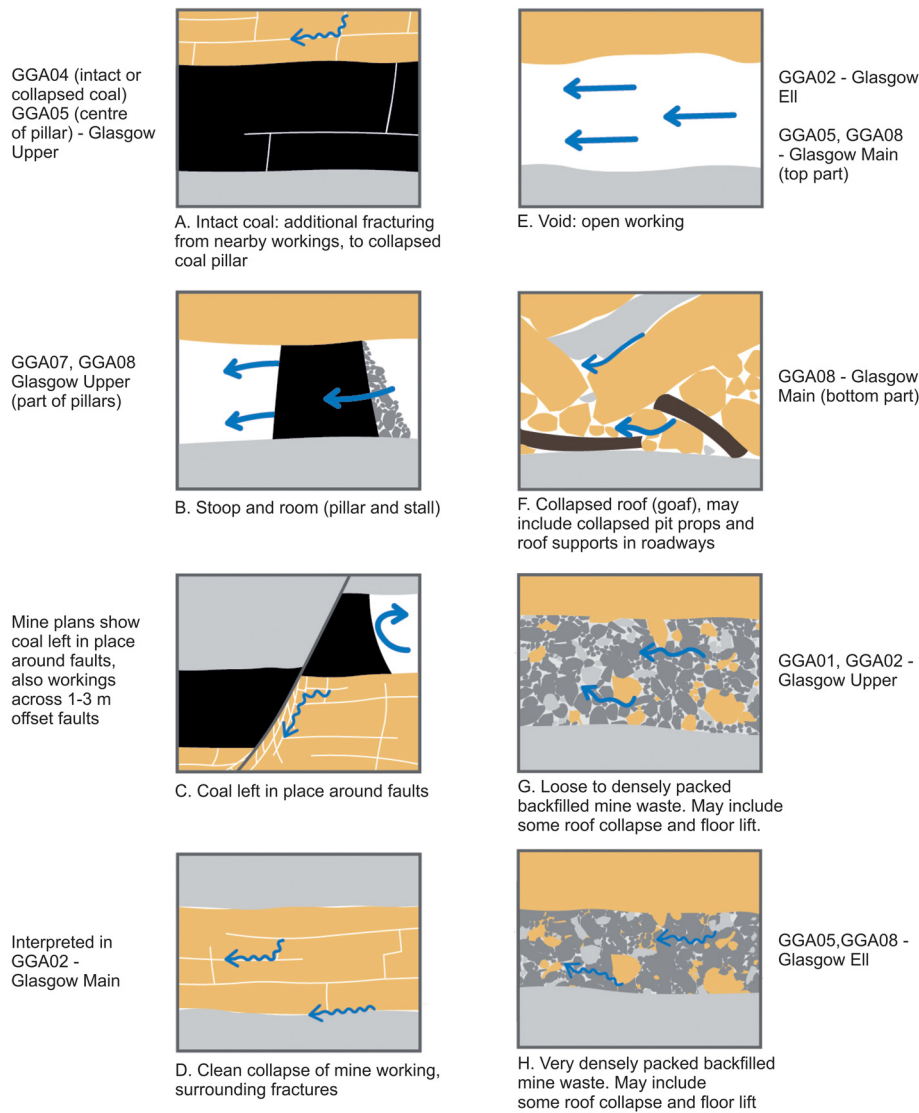


Fig. 10. (a–h) Mine water reservoir classifications observed at the Glasgow Observatory with indications of their influence on hydraulic properties. ©BGS, UKRI 2021.

probably have enhanced transmissivity compared with unmined bedrock but not so great that heat would be dispersed too widely.

These initial results from the Glasgow Observatory highlight that although there is great variability in mine water reservoir types, there is resource potential to be investigated within the spatially extensive stoop and room and total extraction mined areas underlying UK towns and cities, as well as the more spatially restricted roadways and shafts. This is important in giving far greater spatial flexibility, as land may not be available, or heat demand may not be present at the locations of shafts and roadways. Boreholes or areas with relatively low yields, low connectivity and recharge may offer heat storage potential.

Exploration risk in locating mine water boreholes

In the same way that uncertainties in lithological heterogeneity, structural configuration and fluid flow pathways form risks for drilling successful conventional exploration wells for oil and gas or for groundwater, the same subsurface variabilities form risks for mine water boreholes. As discussed above, additional uncertainty comes from the complexity of the mine water reservoir and its evolution since mine closure. However, in contrast to other resources, mine abandonment plans, pumping records and historical knowledge provide greater certainty in terms of the resource location (extent and depth) and likely reservoir typologies. Given mine water heat technology is not widely developed, there are

limited data available in the public domain on the ‘success rates’ of mine water boreholes in the UK, nor is there a framework for evaluating ‘success’ (as a borehole unsuitable for heat abstraction may be suitable for re-injection, monitoring or heat storage). Five of the six mine water boreholes at the Glasgow Observatory could be classified as successful in that they are screened across the planned mine working interval with proved yields on initial hydrogeological testing. Longer duration pumping and additional hydrogeological testing would further quantify the boreholes’ ‘success’. The sixth borehole (GGA02) encountered problems during annulus grouting, resulting in it being a ‘dry’ sensor testing hole. Prior to those problems, two mine workings were recognized, but the Glasgow Main mine working target interval was not recognized during drilling, the rock chip returns indicating a presumed clean collapse of the sandstone roof (Monaghan *et al.* 2020c).

Lessons learned during the development of the Glasgow Observatory, based on the above synthesis of pre-drilling understanding and construction phase data, include the following.

- (1) The uncertainty in georeferencing old, creased mine abandonment plans can be greater than the metre-scale variability of stoop (coal) and room (void) workings, making it very difficult to locate a borehole to penetrate either target with certainty. A dynamic drilling programme allowing for responsive decisions is likely to increase success and reduce costs. For example, if some boreholes

are planned for deeper workings and a stoop (intact coal) is encountered, carry on drilling. If a room (void) or void and loosely packed waste is encountered, make that the target interval for that borehole.

- (2) Areas marked on the mine abandonment plan as ‘total extraction’ penetrated a large number of mine water reservoir classifications (open void, waste, fractured rock, clean collapse). With the exception of a void, wood or waste interpreted as a roadway on the abandonment plan, the variability was not predictable.
- (3) More intact coal pillars were encountered than expected in an area marked as ‘total extraction’. This is contrary to predictions of former miners and mine surveyors that in older mines more coal was taken or ‘robbed’ than was recorded.
- (4) For these open-hole, relatively wide-diameter boreholes, use of a borehole optical camera and caliper log was critical in characterizing the mine water reservoir type and height, and in reducing borehole construction risk (e.g. placing of the screened section and rubber annular seal). Cored boreholes could provide similar information, although with less certainty on accurate depths if core recovery was poor, or on changes in the *in situ* mine working condition as a result of drilling.

Success rates for mine water boreholes are likely to vary dependent on the age and quality of mine abandonment plans, the depth to mine workings and the available hydrogeological information. With the available pre-drill information at the Glasgow Observatory location and known variabilities proved in the mine water reservoir from legacy boreholes, a near 100% ‘success’ rate for mine water boreholes to encounter voids was not expected. The Glasgow Observatory experience has shown that drilling programmes designed to be responsive to conditions encountered during drilling are likely to be beneficial. Other approaches might include the drilling of narrow diameter preliminary boreholes (IGA and IFC 2014); however, given the metre-scale variability of mine workings, subsequent appraisal boreholes would need to be co-located. Surface-based geophysical survey techniques may offer useful insights (e.g. microgravity, electromagnetic, magnetic, electrical resistivity tomography or ground penetrating radar surveys as described by Dennehy *et al.* 2019); however, these were not utilized pre-drill in the Glasgow Observatory owing to the building rubble and foundations in the thick made ground and 30–40 m thick superficial deposits.

Conclusions

Boreholes at a subsurface observatory for mine water heat and heat storage research in Glasgow penetrated made ground, a thick sequence of superficial deposits, bedrock and mine workings at depths of around 50–85 m. The bedrock succession exhibited typical heterogeneity of the Scottish Coal Measures Group, whereas glacial to post-glacial superficial deposits proved more sand- and gravel-dominated than predicted.

Although the depth and flooded nature of mine workings was reliably predicted by 1930s mine abandonment plans and legacy boreholes, we document some of the challenges in predicting legacy mine workings and exploration risks. Mine water reservoir classifications proved include open water-filled voids, waste-filled mine workings, coal pillars and the fractured rock mass. The reservoir extends beyond the mine working through 1–2 m zones of fracturing and disturbance. Longer duration pumping is required, but initial hydraulic yields with limited drawdown highlight that ‘stoop and room’ and ‘total extraction’ mined areas offer potential for mine water heat and heat storage resources. With a spatially extensive footprint across former UK coalfields, these types of

legacy mine working allow for greater flexibility in locating boreholes than shafts and open roadways, so classifying and characterizing the resource potential is important. With much still to be investigated on the hydraulic properties and thermal resources of flooded coal mines, this pre- and post-drill geological synthesis of drilling into mines for the Glasgow Observatory boreholes forms a basis for future work, increasing the evidence base around mine water energy for decarbonizing heating and storage towards net-zero carbon emission targets.

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