Method and key observations from constructing a mine water heat subsurface observatory in Glasgow UK

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Method and key observations from constructing a mine water heat subsurface observatory in Glasgow UK

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Summary

The UK Geoenergy Observatories project (UKGEOS) is developing a subsurface Observatory in Glasgow for research and innovation in mine water heat and heat storage. This report provides an overview of the timing and tasks adopted in borehole construction and initial testing. It has been subdivided into three stages: planning/feasibility, exploration and appraisal. The fourth delivery or development stage, which is to construct the above ground infrastructure for mine water circulation and thermal perturbation, is ongoing in 2021 and is not covered in this report.

Land availability, prior land use and environmental protection were key constraints in establishment of the Observatory, as well as subsurface geological factors. These are likely common to many mine water heat projects. Observations made during construction of the Glasgow Observatory are summarised to help to de-risk future mine water projects. These include difficulties associated with completing boreholes through sands and gravels in superficial deposits, and the challenge of identifying the type and size of mine workings during drilling. A key learning was the value of using a downhole optical or acoustic camera to better understand the nature of mine workings prior to screen installation.

1 Introduction

A number of best practice guides and summaries of development phases have been published for the exploration, construction and operation phases of geothermal schemes (e.g. IGA & IFC 2014; de Gregorio et al. 2020). To date, however, guidance for mine water scheme development has generally focussed on the technological aspects e.g. Minewater Good Practice Guide (2013) and Gyzl et al. (2019). There is a lack of documented experience in mine water geothermal project delivery, in particular UK-specific information addressing resource identification, permitting/ regulatory aspects and technical risks. This lack of awareness of *how* to develop mine water geothermal resources is perceived as a barrier to widespread development (NERC et al. 2019).

The UK Geoenergy Observatory in Glasgow is a UKRI/NERC field facility for research and innovation in mine water heat, heat storage and assessment of any associated environmental effects. The Glasgow Observatory has commonalities in its coal mining history, geology and legacy of industrial land use with other parts of the UK. The design is similar to a small mine water heating scheme that may be constructed to provide localised district heating or to supply a single building. The main difference is that the Glasgow Observatory does not have an end user for heat supply and is not designed to prove the economic case. It is a research facility that offers flexibility to test various processes, measure parameters and test technologies that would not be possible within a heat supply scheme.

This report provides an overview of the borehole construction and initial testing of the Glasgow Observatory, which correspond to the feasibility, exploration and appraisal stages of a mine water heat scheme. The installation of heating/cooling infrastructure is due to occur in late 2021 and is not covered here. Experience gained during Observatory construction is summarised to help to de-risk future mine water projects and aid in the development of best practice. This report is not meant to be used as best practice guidance, or as a comprehensive workflow or checklist.

2 Summary of the Glasgow Observatory

The Glasgow Observatory is located in the south-east of Glasgow city region with the majority of the infrastructure situated within the Cuningar Loop, Rutherglen (Figure 1). The Observatory was designed specifically for mine water energy research and innovation challenges. The planning, construction and testing of the boreholes was delivered between 2016-2020 and the Observatory is planned to have a 15-year operational lifespan. It comprises 12 boreholes across five sites – six are classified as environmental monitoring boreholes including one for recording real-time seismic data; five are designated as mine water characterisation and monitoring boreholes and the final one has been reconditioned as a sensor testing borehole.

The five mine water boreholes are all located within the Cuningar Loop and are screened across the Glasgow Upper or Glasgow Main mine workings to depths of around 50 m and 85 m respectively. The mine water reservoir at the screened section varies significantly between the boreholes including intact coal, voids and packed waste (Monaghan et al. 2020c). The sensor testing borehole (GGA02) was originally planned as a mine water borehole but due to grout ingress, the targeted Glasgow Main mine working is no longer accessible.

The environmental monitoring boreholes at Cuningar Loop have drilled depths ranging from 16 m, screened within the shallow superficial deposits, up to 45 m screened in the bedrock above the Glasgow Upper mine working.

The 11 boreholes at Cuningar Loop have a similar design, adopting three strings of casing which decrease in diameter with depth (Figure 2). The surface casing and the casing through the superficial deposits are steel. The bedrock casing which includes the screened section is UPVC in composition.

The top sections of the boreholes, varying in depth up to 18 m bgl, were drilled using a piling rig with auger which was selected to increase the possibility of successfully drilling through the made ground. Once the surface casing had been installed, the drilling technique was changed to rotary drilling for the superficial and bedrock sections, with the initial plan to drill open hole and install casing at the end of each section. This was subsequently altered for several of the boreholes when thick sands and gravels were encountered in the superficial deposits and “duplex casing whilst drilling” was used to prevent hole collapse and complete the casing installation.

Initially all shallow mine workings encountered in a borehole had to be sealed before drilling to greater depths could commence. This was due to regulatory and science requirements to ensure that the borehole was not a pathway to mixing of groundwater of different quality between the various levels of mine workings. This process was costly both in time and money. The requirements to seal the mine working prior to drilling to the deeper mine working was removed once it was ascertained that the mine waters from each working were chemically similar. All workings were sealed once the casing had been installed.

The mine water boreholes are all equipped with permanent downhole electrical resistivity tomography (ERT) sensors and fibre-optic cables for distributed temperature sensing (DTS) to give a four-dimensional picture of the subsurface. These were fastened onto the outer casing prior to grouting up the borehole annulus.

The completion of each borehole involved grouting up the annulus. The grout composition was initially designed to be optimal for the ERT (Tarmac Pozament SP/F6) but during the drill campaign the grout mix was altered to bentonite cement pellets in certain sections to decrease the setting time of the mix and to permit the emplacement of a seal across the large voids thus preventing grout ingress into the casing as had occurred at borehole GGA02.

When final borehole cleaning and test pumping had been completed, hydrogeological data loggers were installed into all of the boreholes at Cuningar Loop. The data is manually downloaded monthly.

The deepest borehole at the Glasgow Observatory is located at Dalmarnock, 1.5 km WNW of the Cuningar Loop (Figure 1) and was drilled in 2018. It was drilled to a depth of 199 m and 165.5 m intact core was extracted. It indicated that this area had not been mined (Kearsey et al. 2019). Open hole wireline logs were obtained before the borehole was cased and a string of five permanent downhole seismometers was installed. These provide baseline seismic monitoring which feeds into the UK national seismic monitoring network.

More detail on the boreholes is provided in Table 1 and in the individual data releases (Barron *et al.*, (2020 *a,b*), Elsome *et al.* (2020), Shorter *et al.* (2020 *a,b*), Monaghan *et al.* (2020 *a,b,c*), Starcher *et al.* (2020 *a,b*), Walker-Verkuil *et al.* (2020 *a,b*)).

As of May 2021, there is a range of open access data available from the Glasgow Observatory. Additional environmental monitoring equipment is planned to be installed on the sites at the Cuningar Loop in 2021. These will provide datasets relating to ground motion, soil gas and air quality which will complement the environmental monitoring surveys of soil chemistry, soil gas, ground motion, surface and groundwaters that have been ongoing since 2018 (Bateson and Novellino 2019; Barkwith *et al.* 2020; Fordyce *et al.* 2020; Fordyce et al. 2021).

Permanent surface infrastructure for research into the abstraction and re-injection of mine water and extraction or storage of heat is planned to be installed on four of the existing mine water boreholes in late 2021 or early 2022.

Future work at the Glasgow Observatory is not covered in this report which solely focusses on the planning/feasibility, construction and appraisal stages of the boreholes.

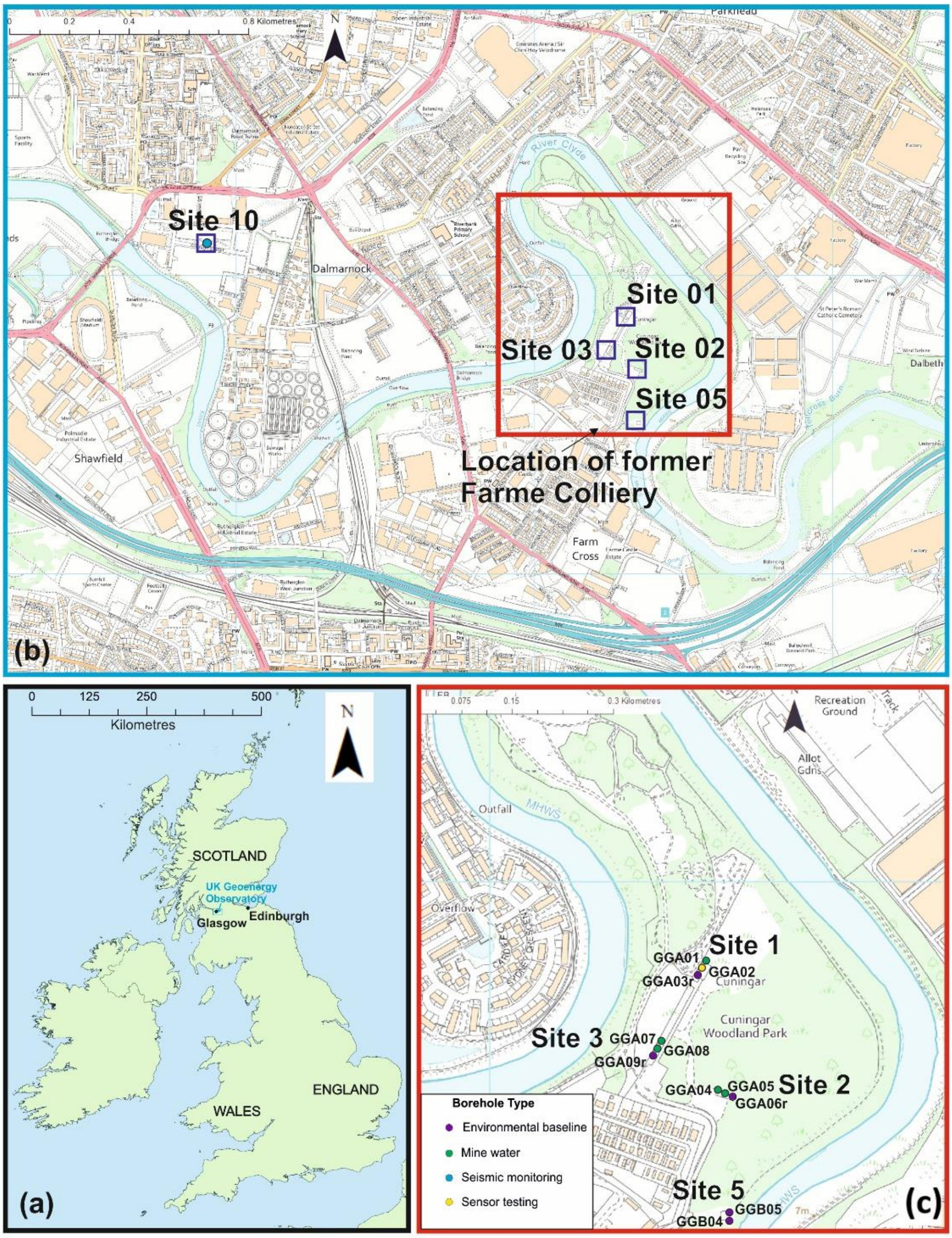
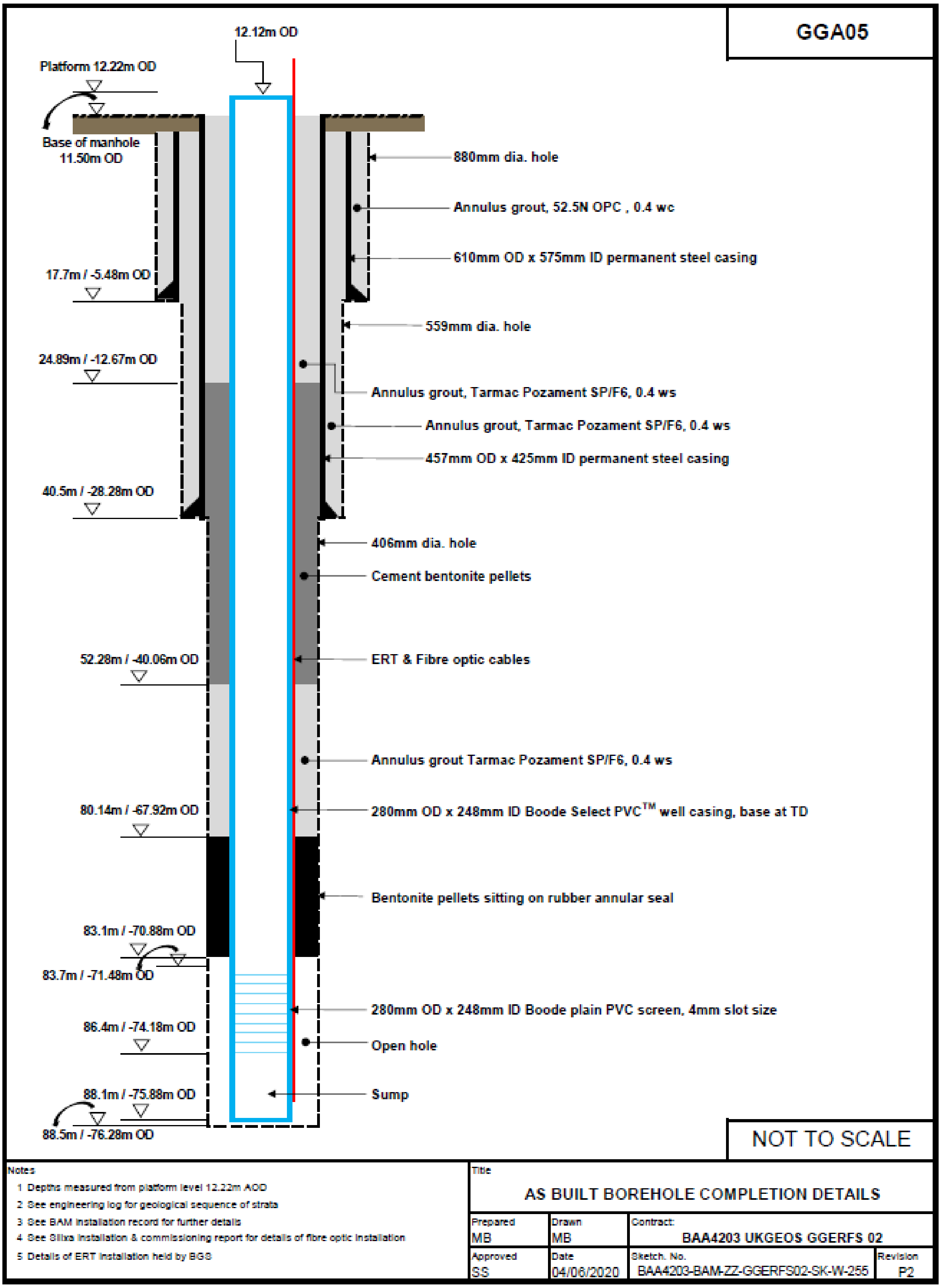


Figure 1 (a) Location of the Glasgow Observatory in the UK (b) position of Observatory sites (c) detail of Cuningar Loop mine water and environmental baseline characterisation and monitoring boreholes. Ordnance Survey data ©Crown Copyright and database rights 2021. Ordnance Survey Licence No. 100021290 EUL.



Notes
1 Depths measured from platform level 12.22m AOD
2 See engineering log for geological sequence of strata
3 See BAM installation record for further details
4 See Silixa installation & commissioning report for details of fibre optic installation
5 Details of ERT installation held by BGS

Title AS BUILT BOREHOLE COMPLETION DETAILS			
Prepared MB	Drawn MB	Contract: BAA4203 UKGEOS GGERFS 02	
Approved SS	Date 04/06/2020	Sketch. No. BAA4203-BAM-ZZ-GGERFS02-SK-W-255	Revision P2

Figure 2 As-built diagram of GGA05. The mine water boreholes were all constructed to the same design. The environmental boreholes that targeted the top of the bedrock were of the same design but were smaller in diameter both for the hole size and casing

Site	Borehole number	Borehole type/ screened interval	Total drilled depth from drill platform level (m)	Screen depth from Boode® UPVC casing datum (m)	Screen type and internal casing diameters	Notable challenges & response
1	GGA01	Mine water/ Glasgow Upper	52.00	44.81 - 48.41	Made ground: 4 mm slotted with pre-glued gravel pack, 248 mm ID	Artesian groundwater – section 3.2.5.10
1	GGA02	Sensor testing	94.16	n/a	248 mm ID	Sealing mine workings – section 3.2.5.7 Grout ingress – section 3.2.5.8
1	GGA03r	Environmental monitoring/ Bedrock	41.72	37.00 - 39.81	3 mm slotted with pre-glued gravel pack, 146 mm ID	Poor superficial deposits sample returns using direct circulation – section 3.2.5.6 Artesian groundwater – section 3.2.5.10.
2	GGA04	Mine water/ Glasgow Upper	53.63	47.40 - 51.00	4 mm slotted with pre-glued gravel pack, 248 mm ID	Monitoring for grout ingress – section 3.2.5.8 Alternative annulus grout composition, essential vs nice to have – section 3.2.5.8
2	GGA05	Mine water/ Glasgow Main	88.50	83.60 - 86.30	4 mm slotted no gravel pack, 248 mm ID	Change in drilling fluid to complete superficial section - section 3.2.5.6 Recognising mine workings during drilling/use of optical camera – section 3.2.5.7
2	GGA06r	Environmental monitoring/ Superficial deposits	16.00	11.79 - 13.76	1 mm slotted with pre-glued gravel pack, 103.8 mm ID	Hole collapse at base of borehole – section 3.2.5.6
3	GGA07	Mine water/ Glasgow Upper	56.90	50.91 - 53.61	4 mm slotted pre-glued gravel pack, 248 mm ID	Poor superficial deposits sample returns – section 3.2.5.6
3	GGA08	Mine water/ Glasgow Main	91.37	85.08 - 87.78	4 mm slotted pre-glued gravel pack, 248 mm ID	Challenges in casing superficial section - section 3.2.5.6 Challenges in drilling sump and impact to fibre optic installation – 3.2.5.10
3	GGA09r	Environmental monitoring/ Superficial deposits	16.00	11.43 - 13.33	1 mm slotted with pre-glued gravel pack, 103.8 mm ID	Hole collapse at base of borehole – section 3.2.5.6
5	GGB04	Environmental monitoring/ Superficial deposits	16.00	10.09 - 11.99	1 mm slotted with pre-glued gravel pack, 103.8 mm ID	Hole collapse at base of borehole – section 3.2.5.6
5	GGB05	Environmental monitoring/ Bedrock	46.00	42.39 - 44.19	3 mm slotted with pre-glued gravel pack, 146 mm ID	Challenges in casing superficial section - section 3.2.5.6
10	GGC01	Seismic monitoring	199.00	n/a	76.6 mm ID	No major issues encountered

Table 1 Summary of Observatory boreholes. Grid references, drilled and datum heights are given in open data downloadable at ukgeos.ac.uk. n/a=not applicable. All depths in table are metres below the datum level stated (mbgl) and rounded to two significant figures.

3 Method and key observations from constructing a mine water heat subsurface observatory

This report provides an overview of the stages involved in the construction of the Glasgow Observatory (Figure 3). They correspond to the feasibility, exploration and appraisal stages of a mine water heat scheme and the equivalence to other geothermal workflows is shown in Table 2. Key observations made during the Observatory construction are summarised to help to de-risk future mine water projects and aid in the development of best practice

Each of the sections below is subdivided into two parts: the first focussing on information and methodology specifically relating to the Glasgow Observatory delivery and the second providing a summary description of the key observations made during each stage.

IGA & IGC (2014) Exploration best practice	Crowdthermal phases (in De Gregorio et al. 2020)	Delivery phase for Glasgow Observatory
Preliminary survey	Project definition	Planning, feasibility, site selection, initial resource characterisation, preliminary survey
Exploration	Exploration	Exploration: permissions and permits
Test drilling	Drilling	Drilling, construction
Project review and feasibility	Resource development	Appraisal: borehole testing, resource characterisation
Field development		*(Development - geothermal infrastructure)*
Power plant construction	Construction	*(Construction)*
Commissioning		
Operation	Operation	*(Operation)*
	De-commissioning	*(De-commissioning)*

Table 2 Summary of high-level stages in geothermal exploration and construction workflows, with workflow phases covered in this report (future stages bracketed in small italics).

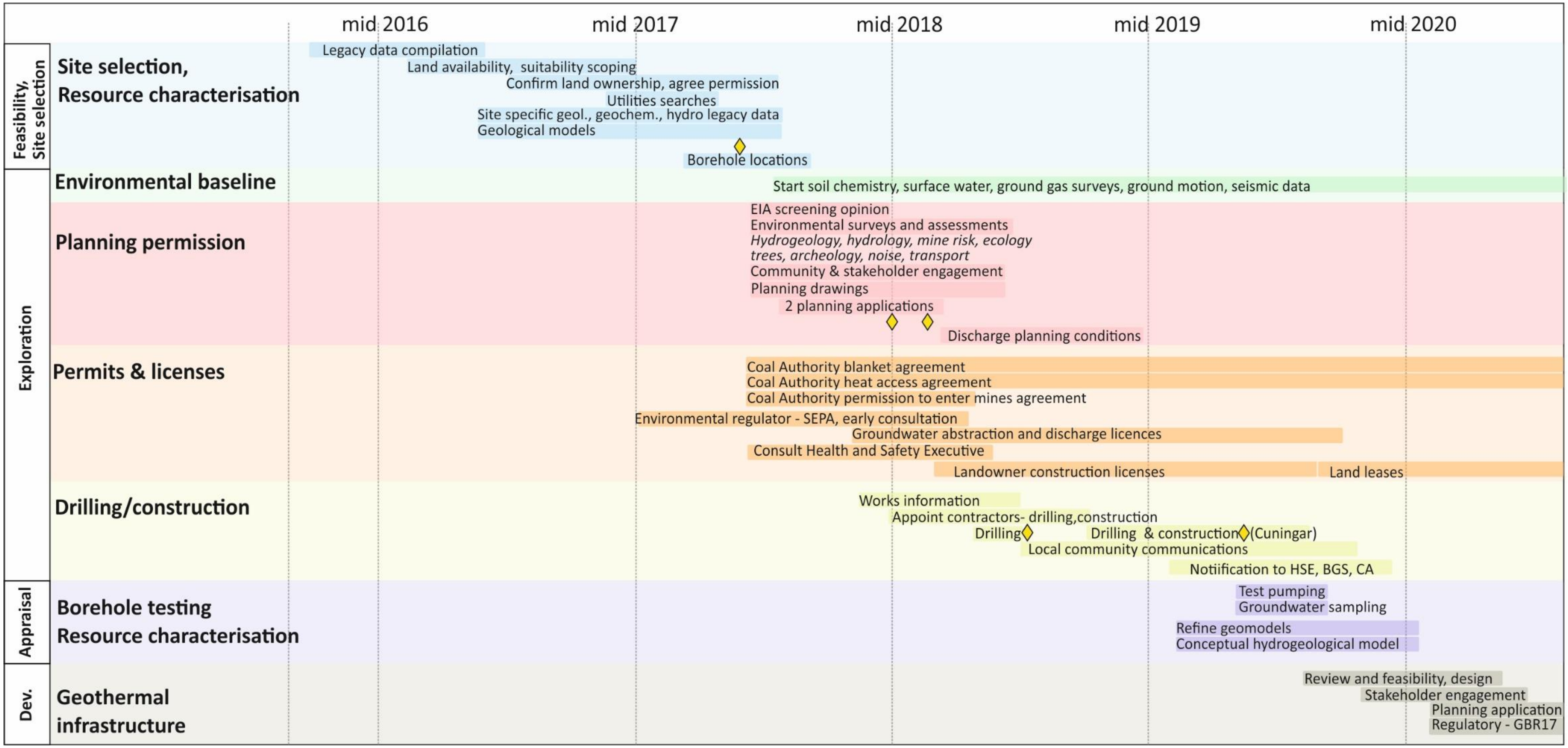


Figure 3 Overview of the delivery timeline for the Glasgow Observatory including the stages of feasibility/site selection, exploration, construction, testing and the initial steps in the development stage. Yellow diamonds represent key milestones, stronger coloured boxes represent the approximate time taken or time valid for (in the case of licences) Dev.=development.

3.1 FEASIBILITY AND SITE SELECTION STAGE

Site selection and feasibility assessment for the Glasgow Observatory commenced in 2016 and 2017 with compilation of legacy data, site selection and initial resource characterisation.

3.1.1 Site selection and initial resource characterisation

Most geothermal heat schemes start with either delineation of an area of interest based on heat demand, or the knowledge of a site with high resource potential (e.g. mine water gravity drainage point or existing mine water pumping station). In the case of the UK Geoenergy Observatory in Glasgow, the project started with an approximately 4 by 5 km location within the Clyde Gateway Urban Regeneration District in the east end of Glasgow and Rutherglen (Monaghan et al. 2017) chosen by an academic-industry Science Advisory Board and UK Research Council project board after a regional screening exercise. Key to this location was the post-industrial, urban coalfield setting representative of a typical location for a mine water heat scheme. Together with the technical challenges of former land use, land contamination and limited land availability, urban regeneration and fuel poverty form the backdrop in common with many former coalfield areas.

Once the area of interest was selected, it was necessary to identify individual sites where construction of a research observatory could occur. Site selection for the Glasgow Observatory commenced in 2016 with geological data synthesis and a literature review as reported in Monaghan et al. (2017).

Important subsurface information for site selection for mine water heat schemes is illustrated in publications such as Mine Water Good Practice Guide (2013), Ramos et al. (2015), Loredo et al (2016); Banks et al. (2017); Farr et al. (2020) and includes:

- Regional hydrogeological and hydrogeochemical data
- Presence of flooded abandoned mine workings
- Water levels in the mine workings and bedrock
- An understanding of the groundwater flow direction
- Pumping rate information from mine dewatering
- Presence of shafts

In the UK, a large proportion of the required subsurface information resides within data centres at The Coal Authority and British Geological Survey as well as local authorities, environmental regulators and research papers. More information for geological characterisation and the regional hydrogeological system than may normally be the case was available for this project from the BGS Clyde Urban SuperProject (for example 1:10,000 scale geological models, BGS digitised mine plans, soil and stream sediment surveys (Monaghan et al., 2014, 2017; Fordyce et al., 2004, 2012, Kearsey et al. 2019b, O Dochartaigh et al. 2019) and various publications (e.g. O Dochartaigh et al., 2011, 2015). However local hydrogeological and hydrogeochemistry data on the bedrock and mined bedrock was notably lacking, and due to the age of the mines (1810-1934) there was a dearth of information on mine water pumping data and shaft conditions.

In tandem with geological data synthesis, a preliminary scoping exercise commenced to identify the key requirements for the observatory. At this stage the proposal was broad comprising a design focussed on a central triangle of sites containing nine mine water boreholes and a set of “outer” sites to host environmental monitoring boreholes. Stakeholder engagement commenced on the scope of the Observatory, and the search began for available land. Along with two local authorities, the engagement of the Clyde Gateway urban regeneration agency was critical, as they provided a range of potential sites undergoing redevelopment for evaluation. In March 2017, the business case for the UK Geoenergy Observatories was approved and in June 2017 a site selection evaluation took place of four sites using a scoring matrix to evaluate:

- Land availability and access
- Presence of multiple mine workings, depth to workings, connectivity of workings
- Locations of nearby unmined ground for baseline monitoring and the acquisition of a geological reference section
- Potential land contamination – obtained from previous land use information

- Concerns on impact for local residents and businesses – noise, visual
- Power, internet connections. Security. Ease of water disposal.

The Cuningar Loop area was chosen for the mine water borehole array because it contained stacked mine workings of various depths and types, had suitable land available with feasible access routes and prior land use was known. At that time, four smaller outlying sites were earmarked for baseline monitoring boreholes, though later in 2018 they were descoped for cost reasons.

3.1.2 Key observations on site selection and initial resource characterisation

- Public engagement and surface factors were of at least equal importance to geological resource factors
- Finding and agreeing available parcels of suitably-sized land in an urban regeneration area was challenging
- Land availability changed rapidly in a regeneration area over timescales of months-1 year and so several options were needed.
- Any land selected needed suitable access routes – many available parcels of land were hemmed in by buildings or other infrastructure and access was difficult.
- The borehole drilling and construction phase used larger parcels of land than the final boreholes, as space is needed for staff facilities and movement of drilling rigs etc. For example, at least 50 by 30 m was needed for a 3-borehole research compound.
- The timing of drilling and construction needs to be considered in relation to other site development projects that are planned in the area
- Borehole locations and access routes should be optimised to not sterilise land for future regeneration
- Prior land use in a former industrial and coalfield area adds additional challenges with specific sites suffering from land contamination at various stages of remediation, or from shallow mine workings or shafts that pose a potential subsidence hazard. Thorough review of ground conditions at an early stage is important.
- The early and continued engagement of key stakeholders was important to a successful outcome. In the case of the Glasgow Observatory this included local Government, devolved Government, regeneration agency, the environmental regulator (Scottish Environment Protection Agency (SEPA)) and The Coal Authority stakeholders.
- Site selection should be based on all available geological and hydrogeological data. At the Glasgow Observatory, the large number of legacy borehole records held by BGS and the high quality of the mine abandonment plans resulted in a reasonably good understanding of the 3D geometry and possible collapse state and fill of the mine workings during site selection.

For mine water heat supply schemes, the location of heat networks and heat demands would clearly place additional constraints on site selection.

3.2 EXPLORATION STAGE

The exploration stage included gaining planning permissions and regulatory approvals, with drilling of the first borehole in late 2018. Construction of the eleven boreholes at Cuningar Loop took place in 2019, with hydrogeological testing and resource appraisal in early 2020. For the Glasgow Observatory, the permission and permitting activities proceeded in conjunction with detailed design and specification of works information to minimise time taken (Figure 3).

For the purpose of this report, the exploration stage covers planning permission/permitting/licencing; environmental baseline surveys; pre-drilling design work; drilling and site construction.

3.2.1 Planning permission, permitting and licenses

Following a design process to define preliminary borehole locations, depths and surface infrastructure requirements, permissions were required from a number of organisations (Figure 3). These were specific to the UK and Scottish regulatory and planning regime, but likely representative for similar projects as they involved an environmental regulator, mine-specific agreements and permissions for permanent surface infrastructure. Given these can be time-consuming to obtain, it proved important to identify them at an early stage.

Planning permissions for the Glasgow Observatory were obtained under the Scottish planning system from Glasgow City and South Lanarkshire Councils covering the permanent surface infrastructure, surface and subsurface environmental impacts during and after borehole drilling and construction. Controlled Activities Regulations (CAR) licences for abstraction and discharge of groundwater came from the environmental regulator, the Scottish Environment Protection Agency (SEPA). Further CAR licensing for boreholes would have been required if the boreholes had been greater than 200 m deep. Permits and agreements were obtained from The Coal Authority to both drill through coal/coal mine workings (‘permission to enter’) and to use the mine workings for heat abstraction/storage (‘blanket agreement’ and ‘heat access agreement’). The Health and Safety executive was consulted and notified. Finally, construction licences and leases were agreed with the Landowner.

These licences and permits all had a range of requirements and constraints associated with them which greatly influenced the design work and construction. The key constraints for the Glasgow Observatory and the resultant changes were:

- Discharge of planning conditions to minimise noise and vibration for local residents, for example solid hoarding used during drilling, the methods used in construction of access trackways to limit vibration, and noise monitoring in place.
- Water environment – borehole drilling and three-casing design to prevent pathways between made (artificial) ground, superficial deposits, bedrock and between different mine workings. Sealing of shallower mine workings during drilling before penetrating to a deeper target mine workings to prevent groundwater mixing until the hydrochemistry and connectivity was understood.
- Drilling methods to minimise environmental impacts – air flush not to be used in the made ground to mitigate against dispersal of materials (e.g. asbestos) and recommendation from The Coal Authority to use water flush rather than air flush in the mined section (mitigating gas movement risk).

Public engagement was an essential part of the planning permission process. A townhall event was held for the local community to explain the rationale behind the project in 2017. More detailed discussions with the local residents were also held to understand their concerns and to address them during the planning stage if possible. The UK Geoenergy Observatories project was fortunate in having a communications specialist.

3.2.2 Key observations on planning and permitting process

- The time (approximately 10 months), cost and effort taken to acquire the permissions and licences for the Glasgow Observatory was considerable (Figure 3). In particular, the breadth of environmental surveys and data (ecology, trees, mine risk, archaeology survey, ground conditions, noise – see Ramboll 2018 a,b) for an environmental impact assessment (EIA) screening opinion and the planning applications was notable. The processes for individual organisations were well documented.
- Ecological aspects can require very specific time windows for surveying, drilling and construction – for example tree clearance is required to avoid bird nesting season. Drilling may not be permitted near protected species locations during their breeding season.
- Local resident views are important and can result in changes to the project scope subject to the outcome of the planning application. In the case of the Glasgow Observatory, one of the drill sites was moved as a result of engagement with local residents and their concerns over noise and vibration during construction.

- Groundwater disposal methods are dependent on the chemistry of the minewater. In the initial scoping phase, this information was not available, so various disposal methods ranging from the best outcome (discharge directly into the River Clyde) through to the most expensive (discharge via tankers to a water treatment plant) were considered. This in turn impacts the cost model.
- Traffic management plans are an important part of the planning approval process. In the Glasgow Observatory a late review of the access arrangements removed the need for construction vehicles to drive into a car park thus reducing the interaction with the general public and local residents. This change resulted in a need to develop revised plans for the local planners and additional work in updating the documents.

3.2.3 Environmental monitoring

In conjunction with obtaining permissions and licences, the geological data synthesis performed in the feasibility and site selection stage was revisited and updated to create a more site-specific geological understanding. Geoscientific environmental monitoring surveys were conducted in the area of the Observatory to provide a baseline prior to construction work commencing. This monitoring may not be a necessity for all projects but the results can provide valuable evidence and risk mitigation for mine water heat schemes. These included:

- Soil gas
- Soil chemistry
- Surface water
- Ground motion (remote sensed)

Prior to drilling commencing at Cuningar Loop in summer 2019, the seismic monitoring borehole at Dalmarnock (GGC01) had been constructed. This strengthened the national seismic monitoring network in the urban area, so that any felt earthquake can be detected and located. Seismic monitoring was active throughout the drilling and construction phase of the remaining boreholes but no notable increase in activity was observed during this period.

3.2.4 Key observations on environmental monitoring

- Separate land access permission arrangements were required to undertake the geoscientific environmental monitoring surveys. These can take substantial time to get in place.

3.2.5 Borehole drilling and construction

The drilling stage has been further subdivided in this report to clarify the various steps needed during any drill campaign and to highlight the key observations in a structured manner.

3.2.5.1 BOREHOLE DESIGN, WORKS INFORMATION AND PRE-DRILL PLANNING

Once the borehole locations were agreed and the principal contractor was in place, the detailed borehole design work commenced in 2018. For the Glasgow Observatory, four different borehole designs were produced – mine water boreholes, bedrock boreholes, superficial deposit boreholes and the cored, seismic monitoring borehole. The preliminary designs were comprehensive enough to enable a scoping cost to be calculated but flexible enough to be changed if required during a later stage of the design work. The borehole design information fed into the full works design produced by the Principal Contractor.

Borehole drilling at the Glasgow Observatory proceeded in two parts due to planning permissions from two different Councils being granted at different times and an urgency to complete construction at Dalmarnock due to subsequent regeneration works and landscaping.

A period of iterations of the work programme and project scope was required during 2018 to comply with planning constraints and available budget. During this process of iterations, three mine water boreholes targeting the deepest mined coal seam and three of the outlying environmental monitoring sites were removed from scope.

At this stage, the detailed designs for the boreholes were revised several times to comply with the evolving science and regulatory requirements. Changes included the confirmation that fibre-optic cables for direct temperature sensing and electrical resistivity sensors in the borehole annulus between the bedrock casing and the rock wall would be installed. This requirement, dictated the diameter of the final section of the boreholes and the length of the sump in the bedrock section due to the dimensions of the termination unit of the fibre optics . Further variations to the design resulted after a review by the drilling subcontractors who made changes according to the capability of their drill rigs and the optimisation of the drill programme. For example, the surface casing was planned to be batch drilled using a piling rig which resulted in an increase in the surface casing diameter. This in turn increased the diameter of the superficial deposits section.

Exercises to ‘drill the borehole’ on paper were undertaken and the various risks and what-if scenarios were identified and discussed between all parties involved in the borehole construction phase. It was particularly necessary to ensure that all contractors understood the science requirements of the project, including data gathering and the collection of during-drilling samples. The geological prognosis for each borehole was provided in conjunction with information about previous ground investigation boreholes but in hindsight more work on the potential variability of the geology could have been completed and communicated with the drillers at this point.

3.2.5.2 KEY OBSERVATIONS: PRE-DRILL EXPLORATION PHASE

- The creation of highly specified works information, appointment and involvement of a contractor drilling team takes many months.
- It is useful to consult with all relevant parties involved in the design and construction early as possible in the design process to save time and prevent the need for unnecessary iterations of the borehole design and programme. In Glasgow, the use of a piling rig for the made ground section was decided at a late stage once the final drilling team was assembled. This resulted in a re-design of the boreholes.
- All risks and related “what-if” scenarios should be captured in the risk register to monitor changes in the scoping cost. If the costs increase significantly either through the requirement for an increased risk allowance, or through revised design work, then a project rescope might be required.
- Mitigations to minimise environmental impact, advice from regulators and science requirements can have significant implications for borehole design and consequently time taken for completion. For example, the requirement to minimise groundwater mixing between artificial ground, superficial deposits, bedrock and different mine workings led to a borehole design of several casings, the annulus of which had to be cemented before the next section was drilled.
- If instrumented boreholes are required, the additional cost needs to consider both the sensors and the specific design alterations that will be required. At the Glasgow Observatory, the width of the termination units for fibre-optic cabling had a significant influence on the size of the casing to rock wall annulus needed, which in turn influenced the borehole diameter and overall cost of drilling.
- The work scope benefits from clearly identifying the project requirements and considering each item in terms of “essential” or “nice to have”. This distinction enables alternatives to be considered if required during borehole construction. In the Glasgow Observatory, the annulus grout was selected to be compatible with the ERT and hence changes to it were assumed to be non-negotiable. After grout ingress occurred at GGA02, it was recommended to use a more viscous mix. This change was agreed by the ERT specialists as faced with the option of continued risk of grout ingress, the science trade off of a potential reduction in the electrical conductivity was deemed to be acceptable
- The borehole cleaning process should be scheduled to occur after all boreholes on one site have been drilled and completed to prevent the requirement for multiple cleaning.

3.2.5.3 BOREHOLE DRILLING AND COMPLETION

The first stage of drilling was the construction of the 199 m cored, seismic monitoring borehole GGC01 at Dalmarnock, Glasgow. It was drilled in November and December 2018 using a Geobore-S coring unit and rig and 165.5 m core was retrieved (Kearsey et al. 2019a). The borehole annulus was fully grouted and the five seismometers were installed into the casing placed at 40 m intervals.

Eleven boreholes were drilled at Cuningar Loop, South Lanarkshire from June-December 2019. Trial pits to understand the made ground composition were dug but there were no dedicated ground investigation boreholes drilled. The borehole drilling and construction is documented in open data releases and reports (Barron *et al.*, (2020 *a,b*), Elsome *et al.* (2020), Shorter *et al.* (2020 *a,b*), Monaghan *et al.* (2020 *a,b,c*), Starcher *et al.* (2020 *a,b*), Walker-Verkuil *et al.* (2020 *a,b*)). The type of mineworking that was encountered in the six mineworking boreholes is discussed in more detail in *Monaghan et al. (2021).* Fibre-optic and the ERT sensors were successfully deployed in the mineworking boreholes during the installation of the casing string.

The final stage of the construction process was to ensure that the boreholes were clean i.e. cuttings/sediment were removed and the borehole was purged of drilling fluids. Boreholes were cleaned using airlift borehole pumps to clear the sump and well screen. Pumping was carried out for two hours with field parameters (conductivity, Ph, ORP, DO, conductivity and temperature) being monitored to check that they had stabilised. More details are provided in individual borehole reports.

The drilling campaign for the Glasgow Observatory encountered several unforeseen problems ranging from borehole instability issues within the thick sand and gravel intervals of the superficial deposits, to issues with the annulus grout influx. Unfortunately, the mine water borehole GGA02 became unusable for its original purpose as during annulus grouting, the grout entered into the cased hole and covered the screened section. The borehole is open to 67.2 m and is available for use for sensor testing. During the construction programme several changes to the drilling method and completion process were made based on the outcomes of drilling the previous boreholes.

3.2.5.4 KEY OBSERVATIONS: BOREHOLE DRILLING

The observations made during the borehole drilling has been subdivided into the following stages: GGC01 cored borehole; Cuningar Loop ground investigation and drilling through superficial deposits; Cuningar Loop drilling into mine workings; Cuningar Loop borehole completion and general lessons.

GGC01: Cored borehole

- Spacers should be inserted into the core boxes at drill site to indicate and preserve zones of non-recovery and the length of time-dependent (e.g. geomicrobiology) samples taken before core curation.
- More accurate cutting of the 3 m core runs into 1 m lengths at drill site and noting of non-recovery intervals would have been beneficial for detailed core management, core scanning and core-log integration

Ground investigation and drilling into superficial deposits

- Drilling of the made ground with the piling rig proved to be a successful method for penetrating the complex anthropogenic deposits including bricks, cement, wood etc.
- Prediction of geological risk during drilling is difficult even when legacy data is available. Differences in borehole diameter, drilling techniques and localised variations in geology may result in unforeseen issues. The detailed geological review of the legacy boreholes in the southern part of the Cuningar Loop did not indicate significant drilling risks in the natural superficial deposits. However, hole instability in the lower sands and gravels of the superficial deposits (27-30m) was encountered in three boreholes (GGA07, GGA08 and GGB05) and hole collapse at the base of the three dedicated superficial deposits

boreholes (GGA03r, GGA06r and GGA09r) was also observed. This led to significant challenges in setting the casing string.

- Duplex drilling (casing whilst drilling) was eventually identified as the preferred method to minimise the risk of hole collapse in the superficial deposits. However, in the Glasgow Observatory, the adoption of duplex drilling was not immediate. For several of the boreholes, the drilling method was changed from normal to reverse circulation rotary drilling to direct drilling to try and progress the borehole. Each change took time to set up the rig and resulted in the hole being left open for periods of several hours. Along with the use of water flush, this might have contributed to the hole instability. The decision to use duplex drilling earlier in the campaign may have saved time and money.
- A preliminary ground investigation using narrow diameter ground investigation probe holes may have mitigated some of the drilling challenges encountered.
    - Investigative drilling of the thick sand and gravel sequence in the superficial deposits could have provided an indication of their instability leading to different drilling techniques being adopted, which would have saved time and money. However, the instability of the superficials may not have been apparent from a narrow diameter borehole as indicated by the results of the numerous legacy boreholes.
    - Exploratory core collected during the ground investigation would have provided a complete succession of the superficial deposits. The drilling method strongly influenced superficial deposit returns and few samples were obtained when using direct circulation rotary drilling as the method tended to remove the fines from the samples. The piling rig auger drilling enabled better samples to be collected, as did reverse circulation rotary drilling. The samples collected from duplex drilling were not prolific or well preserved. In the sections drilled using bentonite mud additive, the fluid samples were unlikely to be used for future research projects due to contamination. In general, samples from the superficial deposits were difficult to obtain and a core extracted from a ground investigation borehole may have been preferable.
    - A ground investigation would also have provided information about the depth of the rockhead prior to drilling. The depths were prognosed from nearby boreholes and geological models and had an error range of up to ±6 m. At the time of borehole design this error range was not deemed to be overly large but it later emerged that the depth to rockhead in this area was prognosed to be close to or just deeper than the limit of the piling rig capability. With hindsight it would have been possible to use the piling rig to drill directly to the base of the second casing string as the top bedrock was shallower than the rig limit. This would have reduced the problems encountered within the unstable superficial deposits.

  During the Glasgow scoping exercise ground investigations were deemed too expensive for the perceived gains, given the relatively good coverage of legacy data and the difficulty of site access (need for tree felling etc.) The metre-scale of variability in the superficial deposits suggested that it would have been necessary to drill three ground investigation boreholes per site and co-locate the subsequent boreholes to de-risk the drilling stage, hence increasing the overall cost.

Drilling into mine workings

The Glasgow Observatory boreholes prove variability in the character of the mine workings over short distances ranging from intact coal through packed waste to voids (Barron et al. 2020 *a,b*, Monaghan et al. 2020 *a,b,c*, Starcher et al. 2020 *a,b*; Monaghan et al. *2021*). This is no surprise given the mine plan records and observations of legacy workings exposed by opencast sites. The technical and risk aspects of drilling into mines are covered by CIRIA (2019), The Coal Authority et al. (2019) etc.

- Recognising mine workings during drilling can be difficult especially with large diameter mine water boreholes as the driller is less able to ‘feel’ a change in the rate of penetration. Similarly, the use of reverse circulation does not enable any sudden losses of flush to be observed. It is crucial to have an experienced driller on site with expertise in drilling into mineworkings to work closely with the on-site geologist.

- The prognosis depths and mine plans for each borehole are invaluable in assisting the drill team to identify the mine workings. Within the error of georeferencing scanned, folded paper documents from 1850'-1930's, the mine plans were accurate in terms of the depths and extent of mine workings for the top three worked seams penetrated. Mining experts, such as a former NCB mining surveyor (W McLean pers.comm.), commonly advise that more coal may have been removed than is recorded on mine abandonment plans, for example pillars may have been removed in areas recorded as pillar and stall remaining. However, in the case of boreholes drilled at Cuningar Loop, these hit more intact coal than would be expected – for example GGA07 was in an area marked as total extraction in the Glasgow Upper, but interpreted as the edge of a coal pillar and void.
- The prognosis for each individual borehole should be updated regularly with the ongoing results of the other boreholes in the drill campaign. These revised depths will be more accurate than the initial models and should be communicated to everyone on the drill site to increase the likelihood of recognising the mine workings.
- The sealing of the shallow mineworkings is problematic, costly and time-consuming. As described in section 2, the shallower mine workings were required to be sealed prior to drilling to the deeper target until the water chemistry of the workings was proved to be similar. In the Glasgow Observatory project, sealing of the Glasgow Upper and the Ell workings was required in borehole GGA02 and used cement to "plug" the shallower mine workings. The optimal grout for this work was judged to be Nugrout. The method adopted was to add small amounts of the grout into the void, wait for it to set and then apply the next layer. Issues included the fact that the drilling had appeared to increase the void space from its initial estimate and it was difficult to know when the sealing was complete and if it was successful. If similar requirements were in place for commercial schemes and depending on the resource available and economic model, the shallowest worked seams may be most cost effective to develop. Equally alternative methods such as including an addition of another casing string should be considered, depending on the number of stacked mine workings and desired borehole diameter at the target interval.
- The use of an optical camera and caliper log proved highly valuable in understanding the type of mineworking drilled. At the Glasgow Observatory, an optical camera was first deployed after the grout ingress on GGA02 (see completion section below). It proved to be of great importance in understanding the character of the mine working, fractured rock mass and in setting the annulus seal depth. This step added cost, as at least 24 hours was needed between drilling and the deployment of the camera to ensure that the water was clear. However, the risk-benefit of the camera was obvious in this project and was used on all of the remaining boreholes.
- Scheduling of subcontractors can be problematic due to the uncertainty in the drilling programme timing. Despite identifying the value of a camera downhole, it was not always possible to use it for every mineworking as there were a limited number of companies that offered this service. The rapidly changing drill schedule prevented detailed advance planning and they were occasions when the camera and sub-contractors were not available. This resulted either in delays to the work or a decision to drill ahead without the camera images.
- An acoustic televiewer was considered to provide an image of the uncased section of the borehole, but the diameter of the mine water boreholes (Table 1) was too large for this tool to work properly.

3.2.5.5 KEY OBSERVATIONS: BOREHOLE COMPLETION

- The completion of a number of the boreholes proved challenging and resulted in the loss of one of the mine water boreholes due to grout ingress. Grout entered and set inside the screened section and borehole casing of GGA02, rendering the borehole ‘dry’ and for sensor testing only (Monaghan et al. 2020c). A similar grout ingress into the casing was noted at GGA04 but the issue was identified promptly and mitigation methods were taken to remove the grout quickly and effectively from the cased section of the borehole. Complex fracturing of the mined rock mass may have caused grout loss in the casing annulus of boreholes GGA02 and GGA04 (see Monaghan et al. 2020c, Starcher et al. 2020a). Alternatively, the mechanism of grout loss may have been due to annulus seal failure. To address the issue, three different methodologies were undertaken for the boreholes drilled subsequent to GGA02:

- Grout was added in incremental volumes to the annulus. In GGA02, the full volume of grout was added in one stage and it is possible that the weight of grout within the annulus may have been partially responsible for the observed ingress into the casing whether via fracture or seal failure. The subsequent boreholes were grouted in several stages and the volume of grout added to the annulus measured. The measurement of the volume pumped into the borehole compared to the expected height of the grout column is more accurate than simply measuring the head of grout as it can provide a quick indication of any losses to the formation/cased hole.
- Regular checks of the inside of the casing string were made throughout the grouting. This enabled any possible grout leakage to be observed quickly (e.g. GGA04 see Starcher et al. 2020a) and prevented the loss of any further boreholes. A pressure resistant pH. meter or conductivity meter can be deployed at the base of the borehole during grouting to detect any grout ingress, as grout ingress significantly changes these properties.
- Use of a more viscous, quick setting grout was used in the later boreholes. The initial SP/F6 grout had been selected due to the electrical and thermal conductivity of the mix deigned for optimal performance of the ERT sensors. This grout was slow to set and had a low viscosity. After the grout ingress problem in GGA02 occurred, bentonite cement pellets were used as they were easy to drop into the borehole and swelled in-situ providing a quick setting seal.

3.2.5.6 KEY OBSERVATIONS: BOREHOLE CLEANING

- The scheduling of the borehole cleaning within the overall drilling programme is important to prevent unnecessary repeated cleaning. In Glasgow the original plan had been to clean each borehole once completed but it was recognised that drilling of adjacent holes could affect hydrogeological conditions in those already completed. To minimise rig downtime, the drilling programme changed significantly during construction and boreholes on each site were not completed in the planned order. Taken together, this meant that the timing of borehole cleaning was changed, and did not take place until the end of the drilling phase at a site.

3.2.5.7 KEY OBSERVATIONS: OTHER

- Minimising rig downtime is very important to keep costs on track, so on a site with multiple boreholes and casing sections, the schedule can be optimised by moving the rig. For example, at the Glasgow Observatory all the artificial-superficial sections were drilled, cased and the annulus grouted before moving onto the deeper superficial-bedrock section. A flexible approach with drilling was also helpful when there were delays with specific items (e.g. fibre-optic cables).
- Despite the extensive pre-drill geological planning the postulated ‘what if’ scenarios were too conservative when it came to the sealing of the shallower mine workings and also in the effect of the unforeseen mobility of sand and gravel in the superficial section. The lesson learnt was that during drilling it is necessary to ”expect the unexpected”.
- The drilling programme at the Glasgow Observatory varied from plans and the “look-ahead” schedule needed regular updating. A number of specialist subcontractors (e.g.

fibre-optics, wireline) needed to be regularly updated about timing. Occasionally the unpredictable nature of drilling progress led to slight delays in getting subcontractors on site, especially around weekends (working days were Monday-Friday).

- The drilling platform level and the casing height was changed several times during borehole construction. The casing top was used as a datum throughout most of the works, but this was cut down at various times causing some difficulty in water level measurements taken at different times and reducing the accuracy for scientific studies. Records of any variation in casing height or manhole chamber floor should be recorded. A lesson learnt was to establish a fixed datum per borehole and provided to all contractors including wireline logging companies, groups deploying downhole sensors and drillers. Ideally the datum could be a trig point in the corner of the site or a construction datum concreted into a location.
- The cutting of the casing should be conducted with care with shavings prevented from falling down the borehole by the use of netting across the open hole. On several occasions fine plastic shavings from the cutting of the Boode UPVC casing fell into the borehole and clogged the pump during borehole cleaning.
- During casing installation, the ERT and fibre-optic downhole sensors were protected through the use of centralisers prevented abrasion against the borehole walls and proved successful in irregular shaped open holes sections. The sensor cables were attached to the casing and to the screened section using gaffer tape and cables ties, which proved effective. A physical mock-up of the casing, sensor cables and centralisers had been constructed prior to drilling so it was possible to see the actual size of each item. The mock-up often worked better than drawings as it helped to understand the flexibility/rigidity of materials.
- The most efficient configuration of ERT and fibre optics is to place the fibre optic termination unit at the base of the borehole. This prevents the need to wrap the unit to ensure that the ERT sensors are not affected by the metal. In Glasgow, all of the boreholes except GGA08 followed this configuration. In GGA08, the termination unit could not be located at the base of the borehole as it was not possible to drill the sump (Barron et al. 2020a).
- A key risk to consider prior to drilling is the likelihood of artesian water and a plan should be developed to manage this risk if it is identified. The presence of artesian conditions in a borehole drilled into the Glasgow Upper mine working in 1979 had been noted. Following a heavy rainfall event in early 2020, two boreholes on Site 1 became slightly artesian, highlighting the value of legacy records. Mitigation has included leaving a longer piece of casing than originally planned.

3.2.5.8 POST-DRILLING CONSTRUCTION

Once the borehole drilling was completed, fenced research compounds were constructed and the area returned to the agreed state as outlined in the planning permission. The various cabinets and plinths were installed and ducts were constructed to enable electrical wires to be deployed when required. The well head chambers were completed and all HSE and as-built information was provided by the contractor to BGS. The final stage of the construction at Cuningar Loop occurred during lockdown due to the Covid pandemic 2020.

3.2.5.9 OBSERVATIONS ON POST- DRILLING CONSTRUCTION ACTIVITIES

- Based on the Glasgow Observatory experience, utility connections (internet, electricity) can take substantial time periods to be approved and installed.
- The construction in the Glasgow Observatory area commenced with work to flatten the ground and to create “platforms” so that the drill rigs would be sufficiently supported. Though the final levels were surveyed, the amount of topsoil removed and gravel thicknesses added were not recorded in detail. The platform heights then changed several times as gravel was removed at various points during the construction phase and after

borehole head works were formed in manhole chambers. The consequence is that the thickness of gravel across the research compounds is not accurately known to a high level of detail that would be useful for a research infrastructure.

- Changes to the original planning permission are time-consuming and incur extra costs. Due to a variation in land use and a requirement for more security, a change to planning permission was needed to include fences around Sites 2 and 3. This was agreed via a planning variation.

3.3 APPRAISAL STAGE

A phase of hydrogeological test pumping followed the drilling of the boreholes. Further appraisal through monthly ground water sampling is ongoing at the time of writing and will be documented in future data releases.

3.3.1 Borehole hydrogeological testing

Having constructed and cleaned the boreholes, it was critical to assess the hydrogeological properties and responses to make an initial appraisal of borehole yields and aquifer connectivity through test pumping. The results informed the design of geothermal infrastructure. The workflow comprised 5-hour step and constant rate pumping tests including monitoring of surrounding mine water and environmental baseline boreholes (Shorter et al. 2021). Test pumping was undertaken after all borehole construction had been completed to ensure that the groundwater regime was not affected by drilling etc. activities.

Water disposal was a major constraint on test pumping. Disposal of water by re-injection into adjacent boreholes was ruled out, as without sealed pipework to prevent ingress of oxygen, iron precipitation could have clogged up newly constructed boreholes. Simultaneous Injection and test pumping in adjacent boreholes would also have prevented a clear understanding of the aquifer water level. Prior to drilling the boreholes, the chemistry of the groundwater was unknown and planning proceeded around the worst case that groundwater would be of poor quality and require to be transported by tanker for disposal in a specialist water treatment facility. Another option investigated was disposal to foul sewer. In the event, geochemical analysis of mine water during borehole construction and cleaning proved the groundwater to be suitable for disposal to the River Clyde in volumes of up to 369 m^3 per day and maximum rate of 20 L/s after passing through tanks to allow settling of suspended solids. A CAR discharge licence was obtained from SEPA on that basis.

The length and rate of test pumping of the mine water boreholes was constrained to five hours by the CAR licence, as well as the test length reasonably achieved in one day allowing for set up and monitoring recovery. The flow rates for bedrock and superficial deposits boreholes were lower such that water disposal volume was less of a constraint.

3.3.2 Key observations on borehole test pumping

- As described above (Section 3.2.2), it is necessary to cost for the worst-case scenario for water disposal. The geochemistry samples from the mine workings obtained during drilling were key to determining the water disposal method. The River Clyde disposal both increased volumes and reduced costs from the worst-case scenario.
- The CAR disposal licence stated the allowed rate/volume limits to the test pumping. The pumping rates were based upon detailed work by hydrogeologists based on yields during borehole drilling and cleaning, to minimise any risks from turbulent flow and significant drawdown of water levels, and to get the best results from the tests. The length of the pumping tests were relatively short due to the constraint of the length of the working day agreed in the planning conditions. In hindsight a slightly higher pumping rate limit may have been preferable (i.e. 25 L/s for five hours) to provide some flexibility, though the number/volume of settling tanks available on site would also have to have been increased in that case. Future research at the Observatory should provide more information.
- Initial indications of the yield of each borehole from purging during construction, and from borehole cleaning were important factors in setting the flow rates for the step test. The

flow rates varied markedly between superficial deposits, bedrock and mine workings as expected. Borehole GGA03r required the flow rate to be reduced and the constant rate test re-run (Shorter et al., 2020a, 2021).

- One of the biggest challenges in the evaluation of the test pumping data has been the reconciliation of the changing datums needed for accurate comparison of water level monitoring of the 10 observation boreholes. These datum changes occurred as the timing of the test pumping was coincident with borehole casings being taken down in stages for the final headworks and the manhole chambers being installed and altered by the addition of cement to the base of the chamber (more detail in Shorter et al. 2021).
- The data from the test pumping, groundwater and mine water geochemistry are key datasets that determine the regulations applicable for future geothermal activities in the next ‘development’ stage, or for abstraction and discharge licences. In the Glasgow Observatory, SEPA have agreed to use a General Binding Rule (GBR) 17 within the Water Environment (Controlled Activities) (Scotland) Regulations 2011 (CAR 2011). For GBR17 to apply, it was necessary to show that water was returned to the same geological formation from which is was abstracted (i.e. the mine workings were part of the same, connected geological formation with similar chemistries), that the chemical composition of the abstracted water would not be altered by geothermal activities and not more than 10 m^3 will be abstracted per day that is not returned (i.e. a sealed open loop system with no additives; see SEPA, 2019).

4 Conclusions

The delivery of the Glasgow Observatory from planning, feasibility and site selection, through to permitting, borehole drilling, construction and testing has taken four years. Whilst several aspects such as the downhole sensor capabilities, open data and extent of environmental baseline monitoring are not typical of commercial geothermal or ground source heat supply schemes, the practicalities of locating and leasing land, obtaining the necessary permissions and permits, challenges in borehole drilling and testing etc. are representative and illustrate that mine water heat schemes can be some time in delivery.

The key learnings from the exploration and appraisal stages of the Glasgow Observatory project can be summarised as follows:

1. Geological subsurface considerations of the ‘best’ resource may become secondary to land availability and access, prior land use and social acceptance in urban areas.
2. Cored ground investigation boreholes could have provided better samples for the superficial deposits and confirmed the depth to rockhead. There is a possibility that these boreholes might have identified the instability in the sands and gravels but this mobility is postulated to be related to the diameter and drilling technique. For maximum benefit, the ground investigation boreholes would have to have been co-located with the subsequent mine water and environmental baseline monitoring boreholes to ensure that the metre-scale variability in superficial geology was captured. This would be too expensive for most projects.
3. As an alternative to a ground investigation, different drilling technologies could have been specified at the outset: one optimised for superficial sediment sample collection (i.e. coring) and one for casing installation in difficult ground conditions (e.g. a higher specification piling rig). With hindsight the casing whilst drilling (duplex drilling) should have been used from the start of the project so that the superficial deposits were not left as open hole for any length of time.
4. Regulatory and science requirements preventing the mixing of mine water from different workings until water quality was proved to be similar added cost/risk to the borehole construction. Sealing of the mine workings before ‘drilling ahead’ proved to be complex and time-consuming. Future projects could consider the use of different casing strings or

further discussions with the environmental regulator on the impact of leaving an open pathway for a limited amount of time until casing installation.

5. The "what-if" scenarios were not broad enough. Information sharing and earlier questioning and scenario planning from drillers and specialist sub-contractors would have been beneficial.
6. The use of a downhole optical camera and caliper log prior to casing installation (open hole) proved to be extremely valuable in characterising the type of mine workings and in setting the position of the screened section.
7. Gaining planning permission, licencing and permits for drilling in to mine workings and abstraction/disposal of groundwater takes a long time, around a year at the Glasgow Observatory.
8. Utility connections (internet, electricity) also proved to take substantial time periods to be approved and installed.
9. The drilling and construction programme at the Glasgow Observatory was adapted to minimise down time and cost. The delivery team learnt to 'expect the unexpected' and be willing to make changes at short notice.

By summarising the stages and key observations made during the construction of the Glasgow Observatory we aim to contribute towards raising awareness and towards best practice for future developers of mine water heat energy schemes.

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