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TECHNICAL ARTICLE

Influence of Mine Geometry and Working Type on Geothermal Exploitation and Thermal Storage

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Abstract
Thermal plumes developed during two heat injection experiments in different flooded mine working levels at the UK Geoenergy Observatory in Glasgow recorded thermal breakthrough times (for 0.1 °C change) of 4.8 and 2.3 days under similar test conditions. Synthesis of the mine abandonment plan, borehole, and outcrop data was used to characterise differences in the mine geometry and working type. New insights on how backfilled, collapsed, and open voids affected groundwater flow and heat transport were obtained from the hydrogeological, wellhead, and downhole direct temperature sensor data measured during and after pumping of the open loop borehole doublets. Over 17 days, heat injection into the Glasgow Upper mine workings resulted in the gradual development of a thermal plume, within an area interpreted to have a greater percentage of backfill and more tortuous flow paths. After 3.9 days, temperatures at the abstraction borehole started to increase at ≈ 0.03 °C/day, with a ≈ 2.3 °C differential maintained 10 days after heat injection and pumping stopped. In the five-day Glasgow Main heat injection experiment, temperature increases after 1.4 days were ≈ 0.14 °C/d, which was interpreted to result from preferential flow and heat transport pathways with less surface area for heat transport through conduction to the rock mass, and quicker transit time to the abstraction borehole. This provides real-world, at-scale quantification for geothermal exploitation and mine thermal energy storage, and demonstrates how mine working type, which influences flow and heat transport, can affect system performance.

Keywords Mine thermal energy storage (MTES) · Groundwater flow · Heat transport processes · Thermal breakthrough · UK Geoenergy Observatory Glasgow

Introduction

Flooded disused mines are successfully being used for mine water geothermal exploitation in projects across the world (Athresh et al. 2015; Chu et al. 2021; Gasperikova et al. 2024; Jardon et al. 2013; Jessop et al. 1995; Korb 2012; Oppelt et al. 2025; Verhoeven et al. 2014; Walls et al. 2021; Wang et al. 2024). Applications for heating and cooling of buildings and in heat networks are proved (e.g. Banks et al. 2022; Coal Authority 2023; Mining Remediation Authority 2025; Walls et al. 2021), and research and development projects are ongoing around mine thermal energy storage (MTES: Deeming et al. 2025; Fraser Harris et al. 2022; Passamonti et al. 2025; PUSH-IT 2024). As a renewable technology with a low carbon footprint, there is substantial potential for growth in the number of mine water geothermal projects to meet net zero emissions targets through decarbonisation of heat and towards more decentralised and secure energy supply (Mining Remediation Authority 2025; Oppelt et al. 2025). Heat networks, including low temperature and 5th generation networks that balance heating, cooling, and storage demands are a current major driver, with countries making sizeable investment (Bussmann et al. 2019; Hahn et al. 2025; Verhoeven et al. 2014). For the growth potential of mine water geothermal to be realised, a range of technical, economic, regulatory and social challenges are recognised, and may be addressed by de-risking, cost reductions,

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streamlining, and awareness raising (NELEP 2021; Oppelt et al. 2025; Walls et al. 2021).

Mine water geothermal energy is unusual in that the location and extent of the anthropogenic aquifer or reservoir is generally well documented in extent, depth and to a lesser extent mining type, by historical mine plans. Drilling to reach the target can be done with high accuracy and success rates (Wyatt et al. 2025); however, the character of the mine workings encountered during drilling can be highly variable. The type and fill of the mine workings influence the pumping response and flow rates achievable from boreholes (Andrews et al. 2020; Banks et al. 2022; Gonzalez Quiros et al. 2024; Monaghan et al. 2022; Receveur et al. 2026a). Whilst pressure responses that occur quickly as pumping starts/stops are more commonly monitored and interpreted (Banks et al. 2022; Shorter et al. 2021), the monitoring, rates and processes that control thermal plumes and rates of thermal breakthrough are poorly documented.

In addition to the pumping rate and borehole doublet design, the long-term sustainability of heat abstracted and stored from pumped mine water largely depends on the flow of groundwater and the active heat transport mechanisms (Loredo et al. 2016; Receveur et al. 2026a,b). Those processes are controlled by the geometry/extent of the mine workings, the mine working type – including post-closure conditions – for example pipe-like flow (in voids), porous media flow (in backfilled waste or collapsed material), and fracture flow (above and below the mine workings) and heat transport via advection and conduction (Guo et al. 2018; Li et al. 2020; Monaghan et al. 2026; Wang et al. 2025). For mine thermal energy storage, there is very limited measured data about the extent of the thermally affected volume in the mine workings and the rock mass, as well as its storage and recovery efficiency. Understanding and predicting the rates and contributions of these processes form technical challenges for mine water geothermal projects, along with the design and location of boreholes and optimum pumping rates to design long-lived, sustainable systems.

The UK Geoenergy Observatory, in Glasgow (UK) (www.ukgeos.ac.uk) is an at-scale facility to study mine water geothermal energy and thermal energy storage in mines. The facility consists of 12 boreholes (five of them screened in two levels of mine workings) and a geothermal centre for flexible experimentation (Fig. 1) (Monaghan et al. 2020a, 2022). The boreholes are equipped with downhole hydrogeological loggers, and those drilled to the depths of the mine workings have installed fibre optic (FO) distributed temperature sensing (DTS), and electrical resistivity cables. The geothermal infrastructure consists of a ≈ 200 kW heat pump / chiller, three different heat exchangers, submersible pumps in two of the mine boreholes screened at two different mine levels (GGA07, screened in the Glasgow Upper, and GGA05 in the Glasgow Main), and reinjection mains in four of the mine working boreholes (GGA01, GGA05, GGA07, and GGA08).

The Observatory can be used to perform heat abstraction or injection experiments with multiple configurations: abstraction-reinjection in the same mine workings, or abstraction from one of the mine workings and reinjection into the other, both in heating and cooling modes. This allows the possibility of performing experiments based on actual supply conditions (e.g. for seasonal thermal storage). The novelty of this work comes from the first multi-day heat injection experiments coupling measured Observatory data to provide new insights on flow and heat transport processes at real-world scale in exceptionally well characterised mine workings. This informs risk reduction on mine related energy installations and provides evidence for regulation and permitting.

In this work, we present the results of two in-seam (i.e. abstraction and reinjection in two boreholes screened at the same mine working level, GGA01 and GGA07 in the Glasgow Upper, and GGA05 and GGA08 in the Glasgow Main (Fig. 1)) heat injection experiments performed at the Glasgow Observatory in 2023 and 2024. First, we summarise our understanding of the geometry, extent, and reservoir heterogeneity in this man-made aquifer from boreholes, plans, and analogue surface exposures to visualise the complexity. Second, with extensive monitoring to measure and monitor thermal plume behaviour, we investigate and compare the response in the two different mine workings to examine the influence of mine geometry and working type on groundwater flow and heat transport.

Method

Mine Water Reservoir Characterisation

A qualitative description of the mine water reservoir was interpreted using a variety of data sources. Up to seven coal seams were worked in the area between 1805 and 1928, with the uppermost three (Glasgow Upper, Glasgow Ell, Glasgow Main) penetrated by the Observatory boreholes in the area of the Farme Colliery. The extent and distribution of the mine workings was interpreted from the available mine working and abandonment plan scans from 1880 and 1930s obtained from the Mining Remediation Authority under licence, and after georeferencing (Monaghan et al. 2022). The analysis presented here includes the identification of the coal seams, working methods (e.g. pillar and stall, total extraction), roadways, faults, and shafts.

Further mine plan analysis then divided the mine workings into zones delineated using both the working method

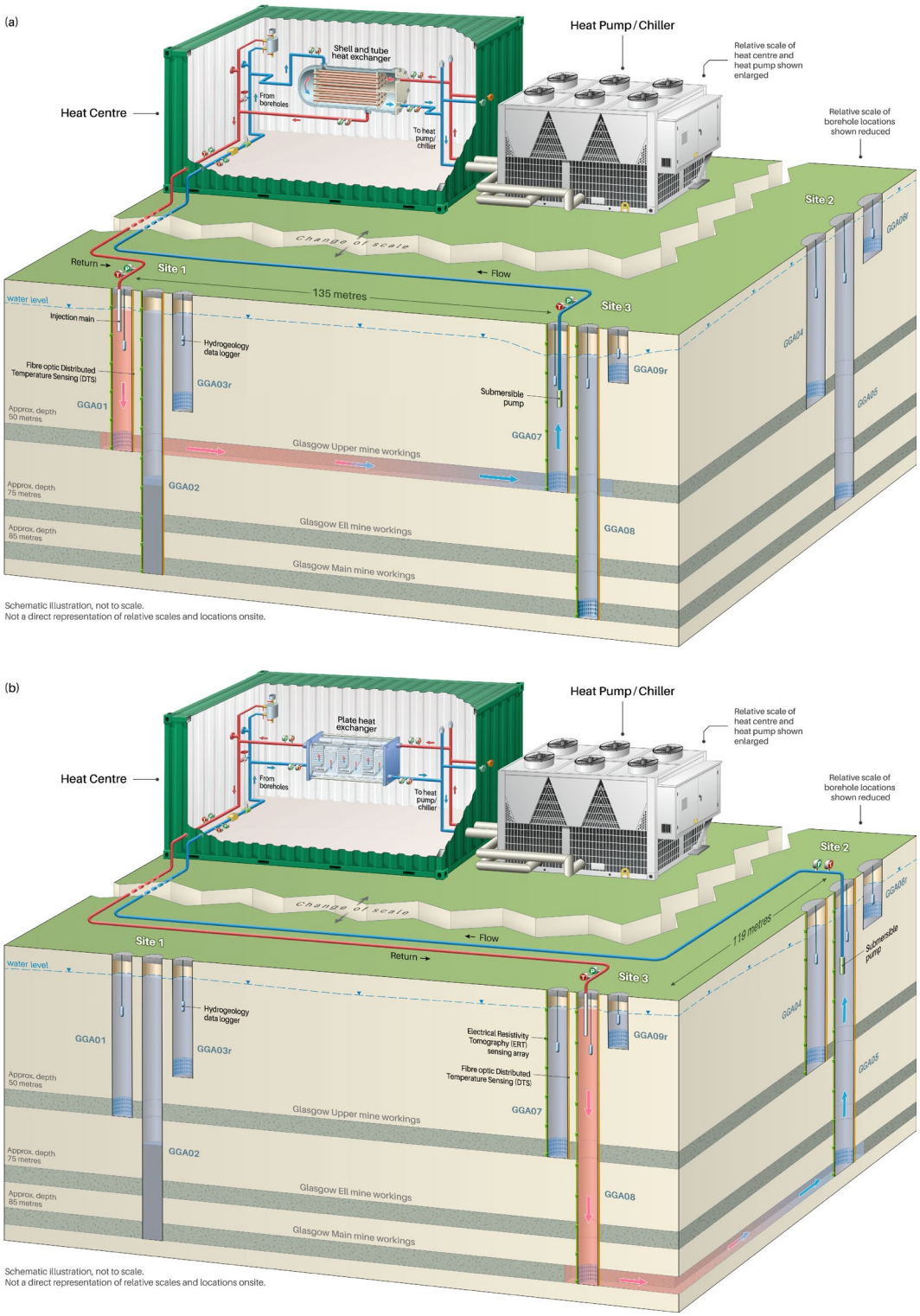


Fig. 1 Schematic diagrams of the heat injection experimental set up for (**a**) the Glasgow Upper and (**b**) Glasgow Main mine workings at the UK Geoenergy Observatory in Glasgow, not to scale. BGS©UKRI 2025

from the mine plan and post-abandonment conditions to interpret the current distribution and properties that influence the groundwater flow and heat transport. The post-abandonment conditions were interpreted using analysis of legacy borehole records, historical mining narratives (Findlay et al. 2020), previous logging of exposed opencast

coal and field sites (author experience 2000–2015; Andrews et al. 2020), and information from the construction of the Observatory that included the drilling of the boreholes, well logging, borehole camera data, and initial hydrogeological testing (Gonzalez Quiros et al. 2024; Monaghan et al. 2022; Shorter et al. 2021). The proportion of 'fill' types within each mine working zone has been estimated, following Monaghan et al. (2022; their Fig. 10):

- Coal: intact in pillars (stoops), cleated, fractured
- Void: water-filled. In roadways with pit props or wooden lining; in pillar and stall workings; in areas with strong, intact roof
- Waste: 'stowage' or backfill material placed into void spaces during mining. Mixed lithologies that are described as 'loosely packed' and have high transmissivity, or can be 'tightly packed' with high clay content, compacted, with low transmissivity
- Roof and roof/pillar collapse material, 'goaf'; large, angular blocks in a variety of orientations
- Fractured rock above and below the mine working, subvertical fractures; as well as subhorizontal separation under 'floor lift' and in the mine working roof.

Table 1 Experimental conditions in the two experiments at the UK Geoenergy Observatory in Glasgow

	Glasgow Upper	Glasgow Main
Start date	12/09/2023 11:00	30/08/2024 12:30
Run time	411 h	121 h 48 min
Abstraction borehole (mine working depth, metres from drill platform)	GGA07 (52.2–53.9)	GGA05 (84.66–85.36)
Reinjection borehole (mine working depth, metres from drill platform)	GGA01 (47.60–48.86)	GGA08 (87.70–90.70)
Distance abstraction – reinjection boreholes at surface	135 m	119 m
Flow-rate	12 L/s	12 L/s
Initial abstraction T (wellhead during pumping)	11.92 °C	12.49 °C
Final abstraction T (wellhead during pumping)	12.51 °C	12.93 °C
Average injection T (wellhead during pumping)	17.37 °C	16.78 °C
ΔT (initial abstraction T – average reinjection T)	5.45 °C	4.29 °C
Heat exchanger	Shell and Tube	Plate
Thermal breakthrough time (0.1 °C change at abstraction wellhead)	116 h (4.8 d)	56 h (2.3 d)
Duration of recovery monitoring	10 d	22 d
Thermal energy injected assuming the average ΔT for the duration of the experiment	113 MWh (at 274 kWth)	26 MWh (at 215 kWth)

At-Scale Heat Injection Experiments

Two heat injection experiments in a doublet mode were performed at the screened mine workings in the Glasgow Observatory as part of the 'Geothermal Energy from Mines and Solar Geothermal Heat' (GEMS) project. The abstraction borehole was equipped with a submersible pump, and a different borehole screened across the same mine working was used for reinjection. The abstracted water was circulated via buried surface pipes and passed through a heat exchanger linked to the 200-kW peak capacity heat pump / chiller to increase the mine water temperature before reinjection (Fig. 1).

The experiments mimicked the heat injection part of an intra-seam mine water thermal energy storage (MTES) system. The aim was to use the exceptional level of characterisation and monitoring to compare and contrast hydraulic and thermal responses in two different mine workings, during and after pumping. Monitoring throughout the experiments was by means of:

(i) Groundwater loggers in the mine water at depths of ≈ 20 m below ground level (i.e. not at the screened mine working level), measuring temperature, pressure, specific electrical conductivity;
(ii) On site barometer and weather station data;
(iii) DTS using FO cables installed on the outside of the casing of the mine water boreholes; and
(iv) Pressure, temperature sensors, flow meter across the heat exchanger, heat pump/chiller and on the surface pipework.

Details of the borehole construction and fibre optic cable installation for the four boreholes used in the experiment is in Barron et al. (2020a,b), Monaghan et al. (2020b, c), Starcher et al. (2020) and the geothermal infrastructure at BGS (2023a).

Glasgow Upper Mine Working

The heat injection experiment using the Glasgow Upper mine workings was conducted in September 2023. The total heat injection period had a duration of 411 h (17 d and 3 h; Table 1) and consisted of an abstraction-reinjection in doublet mode between two boreholes located ≈ 135 m apart at a constant flow rate of 12 L/s. GGA07 was used as the abstraction borehole and GGA01 was used for reinjection (Fig, 1 A), after increasing the water temperature using the heat pump/chiller and the shell and tube heat exchanger.

Glasgow Main Mine Working

The experiment using the Glasgow Main mine workings started at the end of August 2024 and ran for 121.8 h (5 days). Abstraction was from borehole GGA05, and reinjection was at borehole GGA08 (Fig. 1B), located ≈119 m apart. The flow rate was also constant at 12 L/s, but the plate heat exchanger was used in this experiment. The differing duration of the experiment was due to available funding and a different heat exchanger was used due to a temporary problem with a valve.

Results

Mine Water Reservoir Characterisation

Glasgow Upper Mine Working

Building on descriptions in Gonzalez Quiros et al. (2024) and Monaghan et al. (2022), more detailed interpretation was made of the mine geometry, working type, and hydrogeological responses of the Glasgow Upper mine working at ≈ 45–50 mbgl (Fig. 2a), using abandonment plans, boreholes, historical accounts, and hydrogeological test results.

The eight classifications of the coal seam and mine working were mapped geospatially (Fig. 2a, Table 2), showing the complex mine geometry based on an interpretation of the different ages of the mine plan. For example, changes from pillar and stall workings on the abandonment plan, to total extraction areas varies over metres to tens of metres length scale.

To better understand or model flow and heat transport within the different mine classifications, illustrative cross sections have been newly synthesised. These visualise what the flooded mine working may look like today, using borehole logs, downhole camera images, and the authors' (AM, EC) experience of logging exposures in former opencast coal sites across central Scotland (Figs. 3 and 4). The percentages of mine working fill types within the geospatial areas were then estimated using those data and interpretations (Table 2).

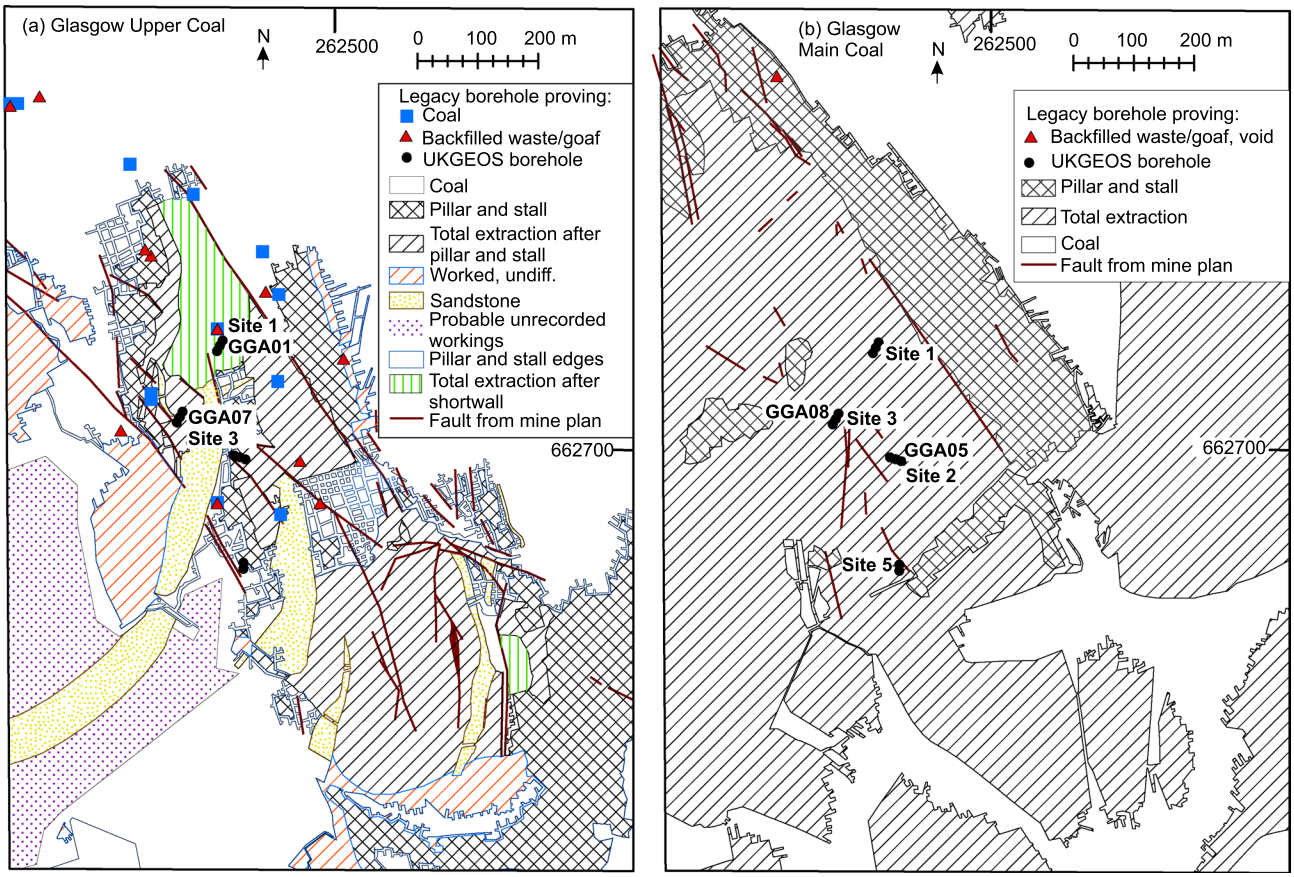


Fig. 2 Map view of the interpretation of (**a**) the Glasgow Upper and (**b**) Glasgow Main mine working reservoir classifications, with location of the UK Geoenergy Observatory and legacy boreholes. British National Grid references shown. Data extracted by BGS from mine abandonment plan scans ©Mining Remediation Authority under terms of licence (CA36/IFTS LICENSING/BGS/16/2). The four Observatory sites are shown on the right-hand figure, with the boreholes used for each heat injection experiment labelled on the map of the mine working they are screened at. BGS©UKRI 2025

Table 2 Summary of mine working reservoir types interpreted and estimated percentages of fill types for the Glasgow Upper (GU) and Glasgow Main (GMA) mine workings in the vicinity of the UK Geoenergy Observatory. Extents on Fig. 2. n/a=not applicable

Mine water reservoir -classification	GU mine working	GU estimated percentage of type	GMA mine working	GMA estimated percentage types
Coal	Poor fracture system within mined areas. Intact coal assumed outside abandonment plan recorded area	100% coal	As for GU	100% coal
Pillar and stall (stoop and room)	Size of stalls (voids) varies from 4–20 m, commonly 5–6 m wide, height ~1.3 m. Interpreted features include pillar 'punching', floor lift, roof collapse and some intact pillars and voids	Coal 60% Void 15% Waste, stowage 10% Roof collapse (goaf) 5% Pillar collapse (goaf) 5%	Stalls (voids) 3–6 m wide, pillars vary from 2–15 m, commonly 4–5 m wide. Height expected ~1.4 m; 1.7 m in NS66SW827	Similar to GU
Total extraction after stoop and room	Drilling proves coal was not totally extracted (e.g. GGA07, GGA08)	Coal 15% Void 13% Waste, stowage 60% Roof collapse (goaf) 10% Pillar collapse (goaf) 2%	n/a	n/a
Total extraction after shortwall	Areas where the 1880's plan shows extracted panels with irregular roadways and total extraction by 1933. In GGA01, GGA02, NS66SW579 was packed with stowage and 'loose' coal	Coal 15% Void 10% Waste, stowage 60% Roof or coal collapse (goaf) 15%	n/a	n/a
Total extraction	n/a	n/a	Total extraction or worked areas with 'waste' label	15% coal, 35% void 35% collapse/ goaf/ waste 15% roadway
Worked undifferentiated	Not specified on mine plans – likely a mixture of shortwall, stoop and room then 'total extraction' e.g. 'void and waste' in borehole NS66SW2647	Not estimated	n/a	n/a
Sandstone or stone 'want'	Erosive, channelised sandstones	Sandstone 100%	n/a	n/a
Unrecorded probable	BGS interpretation of probable workings (due to Ell workings, thick seam, faint traces on the 1880's plan)	Not estimated	n/a	n/a

The area between Sites 1 and 3 is shown as worked out over the area of former NW to NNW-oriented shortwall extraction/roadways according to the 1933 mine abandonment plan; stoop and room workings are shown on the 1884 plan (S3109_1_1; Monaghan et al. 2022; Fig. 6a and b). Borehole drilling proved there was more intact coal than expected at Site 3 (plan S10922_1_6; GGA07, GGA08, Monaghan et al. 2022), suggesting that some stoops/panels of coal remain. Thus, between Sites 1 (GGA01) and 3 (GGA07), some remaining stoops/panels may be NW-SE oriented, resulting in convoluted flow pathways perpendicular to that between the borehole doublet.

Areas of shortwall workings (Fig. 2) have been interpreted to be largely filled with loosely packed stowage based on borehole drilling (mixed rock types with staining GGA01, GGA02; Fig. 3) and do not appear to have collapsed. In contrast, the boreholes at Site 3 proved there was an intact mudstone/siltstone roof with partly intact coal and partly-water filled void (GGA07; Fig. 3).

Intact thicknesses of coal were also observed at Site 2, as well as interpreted fractured coal and fractured sandstone roof (Fig. 4). Legacy boreholes show a similar level of variability including NS66SW579 (waste, loose coal, and stowage), NS66SW2468/R6 (waste), NS66SW631 (void, collapse material above worked coal, waste/stowage), as summarised on Fig. 2.

The fractured rock below and above the mine workings extends the mine water reservoir beyond the mine workings. Borehole images and caliper logs show that fractures propagate above and below the Glasgow Upper mine working, generally for about 1–2 m (Monaghan et al. 2022; Figs. 3 and 4). Fracturing and collapse are well-documented phenomenon, commonly 2–10 times the height of the worked coal (Guo et al. 2018; Healy and Head 1984; Mason et al. 2019; NCB 1975).

Between Sites 1, 2, and 5 (GGA01, GGA04, GGB05; Fig. 2), the former mined roadways and stalls (stoops) are recorded as in similar N-S to NNW-SSE directions (Fig. 6 a

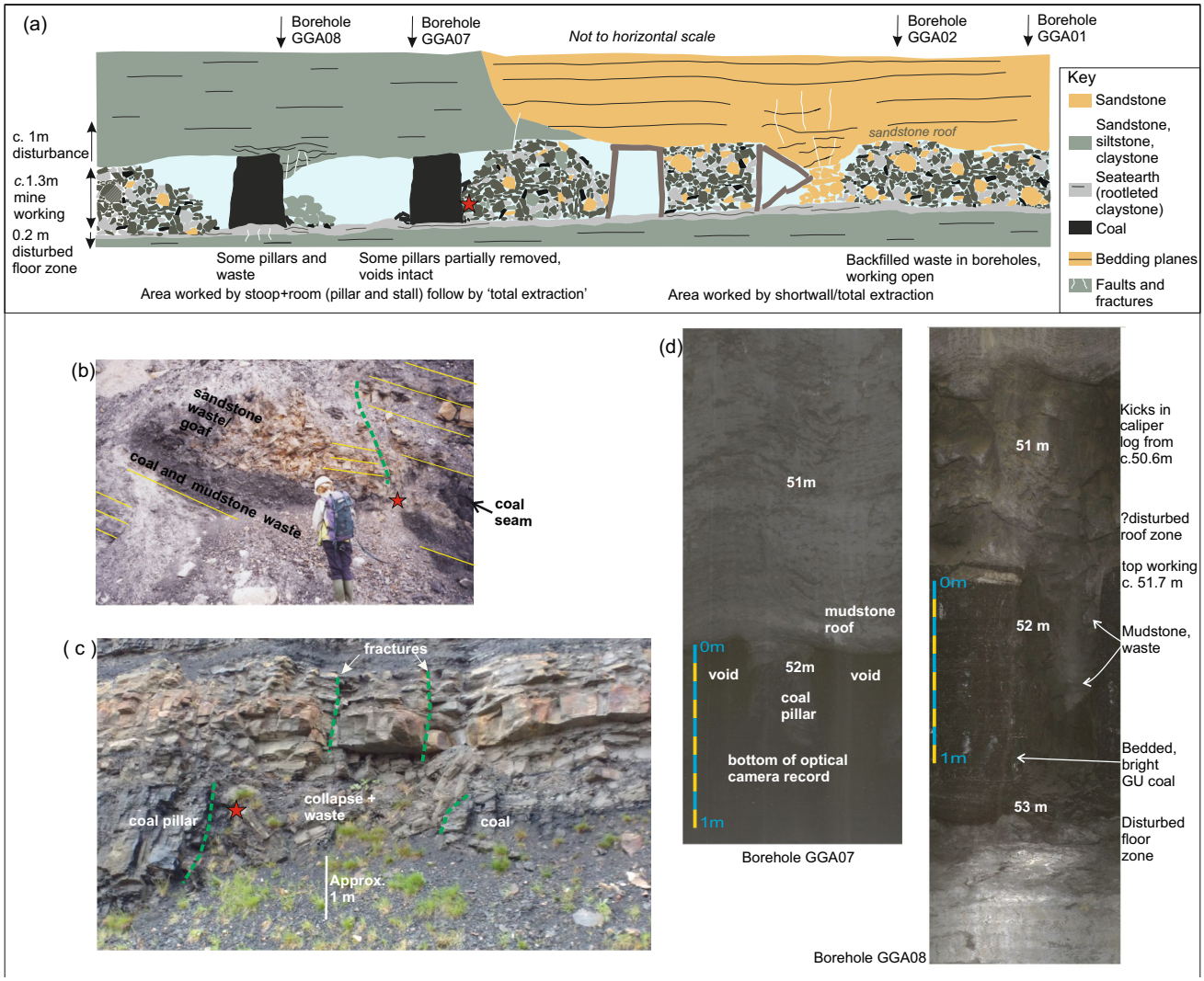


Fig. 3 **a** Schematic (not to scale) interpretation of the mine workings around Site 1 and 3 in the Glasgow Upper mine working based on mine abandonment plan and borehole data, vertically exaggerated. The locations of boreholes penetrating the mine working is indicated. BGS©UKRI 2025 **b** Waste/collapse fill next to coal exposed in Glentaggart opencast coal site, red star indicates similar situation in sketch. Image BGS©UKRI 2003. **c** Waste/collapse fill next to coal exposed in Spireslack opencast coal site in 2018, red star indicates similar situation in sketch. Image BGS©UKRI 2018. **d** Optical camera images of Glasgow Upper coal and mine working from boreholes GGA07 and GGA08, BGS©UKRI 2020

in Monaghan et al. 2022) to the alignment of the boreholes at those sites. If the roadways and stalls remain as open or partially collapsed, they may form preferential flow pathways between the sites. In contrast, a sandstone channel (a 'want' in mining terminology) divides the coal seam and mine working between Sites 2 and 3 (GGA04 and GGA07).

The transmissivity of the Glasgow Upper mine working is estimated to be high based on test pumping of the boreholes (950–1020 m^2/day, Shorter et al. 2021), although the mine working is recorded as backfilled with stowage; this is commonly described in borehole records as 'loosely packed').

Glasgow Main Mine Working

Beneath the Glasgow Upper mine working and Glasgow Ell mine working at ≈ 76 mbgl, the Glasgow Main mine working is the third mined seam at ≈ 85 mbgl. With no legacy boreholes penetrating the mine working within 100 m of the Glasgow Observatory, the new interpretation of the spatial distribution and character of the Glasgow Main mine working reservoir is less certain and relies on mine abandonment plans, three UK Geoenergy Observatory boreholes (GGA02, GGA05, GGA08), test pumping, and hydrogeological monitoring data.

The mine abandonment plans for the Glasgow Main mine working dated 1845 (S3102_3_3), 1924 (S3102_1_3) and

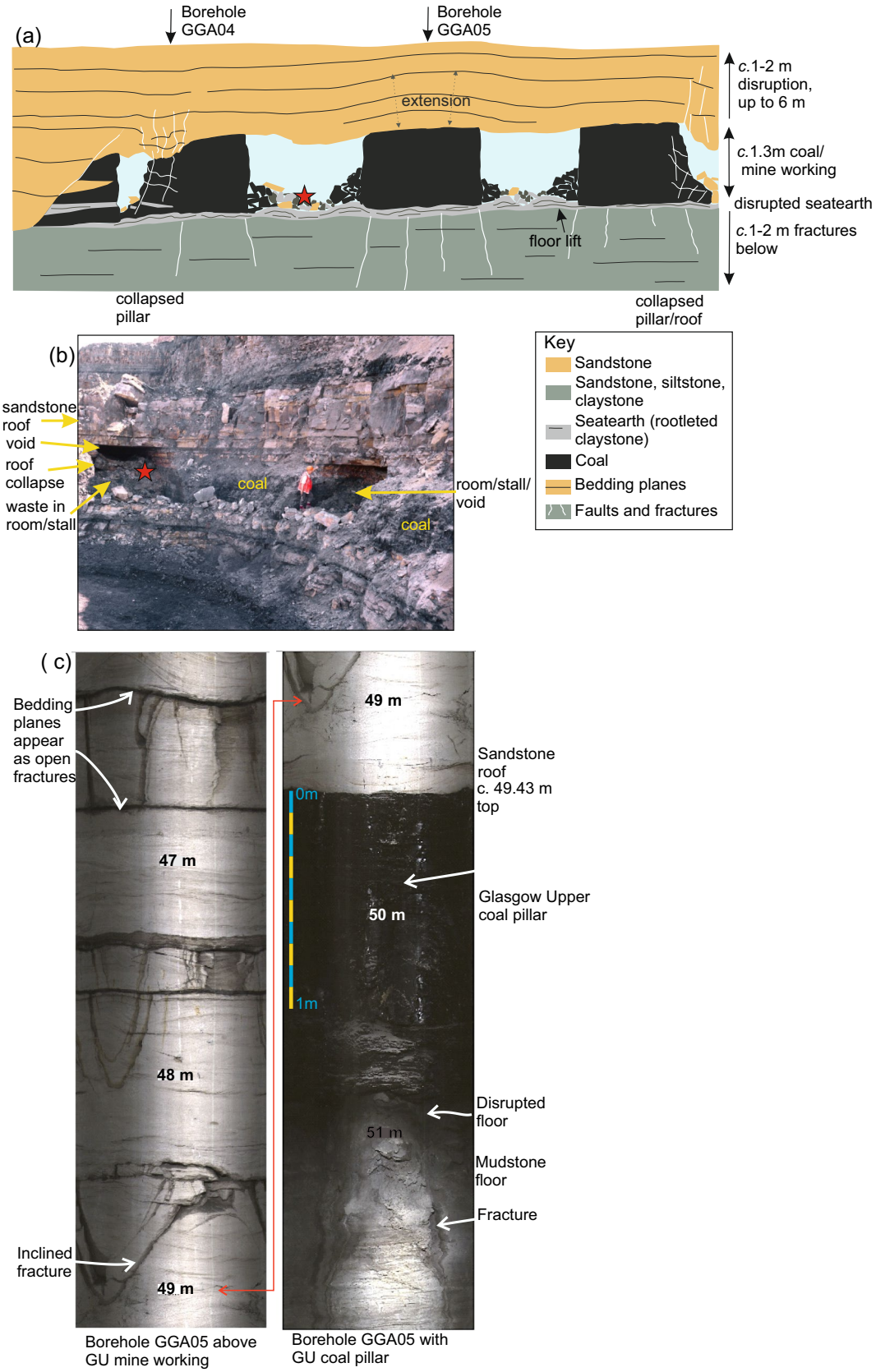

(a)
Borehole GGA04
Borehole GGA05
extension
c.1-2 m disruption, up to 6 m
c.1.3m coal/ mine working
disrupted seatearth
c.1-2 m fractures below
floor lift
collapsed pillar
collapsed pillar/roof
(b)
sandstone roof
void
roof collapse
waste in room/stall
coal
coal
room/stall/ void
Key
Sandstone
Sandstone, siltstone, claystone
Seatearth (rootleted claystone)
Coal
Bedding planes
Faults and fractures
(c)
Bedding planes appear as open fractures
47 m
48 m
49 m
Inclined fracture
Borehole GGA05 above GU mine working
49 m
0m
1m
50 m
51 m
Sandstone roof c. 49.43 m top
Glasgow Upper coal pillar
Disrupted floor
Mudstone floor
Fracture
Borehole GGA05 with GU coal pillar

Fig. 4 **a** Schematic (not to scale) interpretation of the mine workings around Site 2 in the Glasgow Upper mineworking based on mine abandonment plan and borehole data, vertically exaggerated. The locations of boreholes penetrating the mine working is indicated. BGS©UKRI 2025 **b** Example of similar mine water reservoir facies exposed in an opencast coal site, red star indicates similar situation in sketch and photo British Geological Survey image P220021 UKRI 1982. **c** Optical camera image from borehole GGA05 above and over the Glasgow Upper Coal interval. BGS©UKRI 2020

1928 (S10922_3_6) record a wide area of 'total extraction' of the coal seam in and around the Observatory boreholes (Fig. 6d in Monaghan et al. 2022; Fig. 2). Small areas of stoop and room workings are recorded ≈100 m to the west (under the River Clyde) and a large area of stoop and room workings ≈ 80 m to the east, in the footwall of the Blythswood Fault and beneath the River Clyde (Fig. 2). The abandonment plan shows traces of former roadways that were the access routes into the total extraction areas on a variety of orientations, with a number of them running near the two boreholes used in the experiment (GGA05, GGA08). Due to the age of the workings, the 'total extraction' including to the south and west of the Observatory boreholes is believed to have been mined as shortwall panels.

The nearest legacy borehole penetrating the Glasgow Main (NS66SWBJ827) is 480 m away from Site 1 in an area recorded as stoop and room workings on the abandonment plan, the borehole recorded void plus waste. The Glasgow Observatory boreholes proved a ≈3 m void with wood/rubber lining roof and 'goaf' at the floor, interpreted as a roadway (GGA08) and void with sandstone roof and disturbed floor zone (GGA05) (Fig. 5). In the third, the Glasgow Main borehole (GGA02), the mine working was not recognized during drilling and is interpreted as a clean collapse (Monaghan et al. 2020c).

The transmissivity of the Glasgow Main mine workings is estimated at 2000–2100 m^2/day (Shorter et al. 2021), greater than that of the Glasgow Upper mine workings. Gonzalez Quiros et al. (2024) suggested that these high transmissivity values may reflect the existence of voids that remain open in the Glasgow Main mine workings compared to the more heterogeneous nature of the mine workings in the Glasgow Upper. The percentage of void and roadway is estimated at 30% in the Glasgow Main vs. up to 15% in the Glasgow Upper, whereas the Glasgow Upper is estimated to have up to 60% of stowage/waste (Table 2).

Summary of Mine Working Characterisation

The mine working type influences the porosity, permeability, and preferential open pathways in the mine water reservoir, as well as the probable evolution post-abandonment of the mines (collapse, pillar spalling, floor lift, etc.; Healy and Head 1984; Mason et al. 2019, p. 129; Mo et al. 2020; Wuest 1992) or erosion/sedimentation via groundwater flow (Andrews et al. 2020). In turn, these influence the mine water flow and heat transport during geothermal exploitation.

The deeper Glasgow Main mine workings has higher transmissivity, consistent with boreholes screened across open, water-filled voids, compared to the shallower Glasgow Upper mine workings with lower transmissivity and boreholes screened across a range of mine water reservoir types (waste, goaf, fractured coal). Fracturing is observed above both mine workings, as well as below the Glasgow Upper. In addition, the borehole locations used in the Glasgow Upper experiment are interpreted to be perpendicular to any remaining pillars of coal, whereas those in the Glasgow Main experiment are at or close to a number of former roadways in a variety of orientations. In the next section, the measured hydraulic and thermal responses from at-scale heat injection experiments allow the effect of these differences interpreted in the mine water reservoir types to be tested.

Experimental Results

Groundwater Responses

Figure 6 shows the groundwater level responses as hydraulic heads (mAOD) in the Glasgow Upper and Glasgow Main borehole downhole loggers during the experiments, both with 12 L/s abstraction/reinjection flow rates. During the Glasgow Upper experiment, the experiment caused a different response in the abstraction (hydraulic heads decreased, GGA07) and reinjection (hydraulic head increased, GGA01) boreholes. The hydraulic head decreased in GGA07 from 9.02 to 8.50 mAOD (52 cm drawdown) during the first 30 min of the experiment, while it increased from 8.94 to 9.19 mAOD (25 cm increase) in the reinjection borehole GGA01. The other borehole screened across the Glasgow Upper mine workings (GGA04), roughly equidistant to the other two, did not show changes linked to either the abstraction or reinjection. When the experiment stopped, both returned to similar heads as during the pre-experimental conditions. No pressure changes related to the experiment in the Glasgow Upper were measured in the Glasgow Main boreholes. All the boreholes were also affected by centimetric to decimetric natural fluctuations related to atmospheric conditions and precipitation, previously observed and explained in more detail in Gonzalez Quiros et al. (2024, 2025a).

During the experiment in the Glasgow Main, a technical issue at the start of the experiment linked to a GGA01 valve being not fully closed resulted in a short period (75 min) in which the returning water was reinjected through this borehole into the Glasgow Upper mine working. This

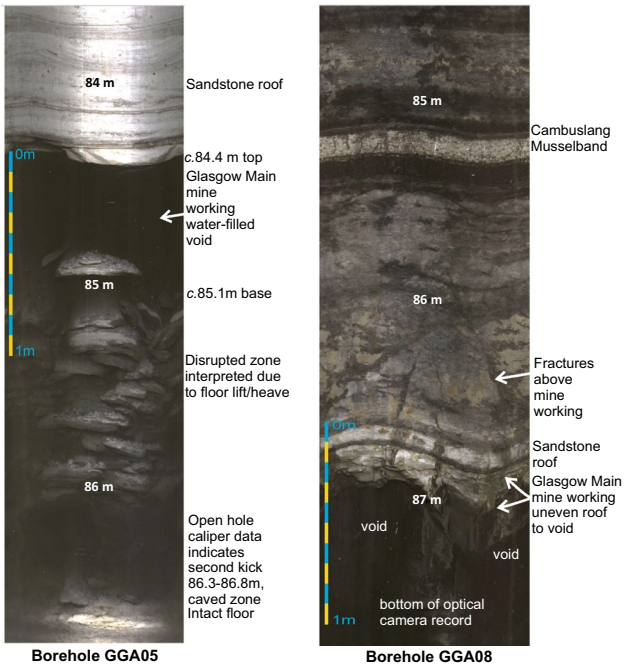


Fig. 5 Optical camera images showing the character of the Glasgow Main mine working in borehole GGA05 and the top of the roadway encountered in borehole GGA08. BGS©UKRI 2020

configuration created a hydraulic head increase in the Glasgow Upper mine workings, observed both in GGA01 with an increase of 0.51 m, and in GGA07 with a head change of 0.23 m. After this was noticed and the valve was closed, all of the reinjected water was redirected to the Glasgow Main via GGA08. During this period, water levels in GGA08 decreased ≈ 7 cm initially. After the valve was closed, water levels in GGA08 increased by 12 cm (5 cm higher than the pre-experiment conditions) and the Glasgow Upper borehole levels recovered to pre-experiment values. At the end of the experiment, stopping the pumping had a very small effect on the water levels, shown in the data as a small decrease in the water level of ≈ 2 cm. The downhole data logger in the abstraction borehole (GGA05) was faulty during the experiment and no pressure data is available. No pressure changes, other than those related to the valve issue at the start of the experiment, were observed in the Glasgow Upper boreholes during the experiment.

Temperature Responses – Wellhead Sensors

Figure 7 shows the temperatures measured at the wellhead sensors of the abstraction and reinjection boreholes during the two experiments. During pumping, these sensors were in direct contact with the mine water flowing past during abstraction or reinjection, and are representative of the temperature at the screened section of the borehole across the mine working. On Fig. 7, the temperature change relative to the initial abstraction temperature is shown (right axis) to facilitate the identification of the thermal breakthrough.

In the Glasgow Upper experiment, the initial abstraction temperature at GGA07 was 11.92 °C. The temperature fluctuated in the first hours, probably due to borehole circulation effects. It first increased up to 12 °C during the first 2.5 h (<0.1 °C increase), returning gradually to the initial values after ≈14 h. Abstraction temperatures then remained at 11.92 °C (±0.01 °C) for ≈ 3 d until it started to gradually increase (Fig. 7a). After ≈ 4.8 d, the measured temperature increase at the abstraction borehole was more than 0.1 °C. It reached a 0.5 °C increase after 14 d and a maximum of 0.59 °C at the end of the experiment, after 17 days. Fluctuations of ≈ 0.01 °C amplitude were observed during the experiment. The reinjection temperature was on average 17.37 °C, but fluctuated between 16.7 and 17.9 °C. Events related to the defrost cycle of the heat pump/chiller resulted in two short periods (<5 min) of cooler injection temperatures that reached minimum temperatures of 9.6 and 10.1 °C (Fig. 7a).

In the Glasgow Main experiment, the initial abstraction temperature measured at the wellhead was 12.49 °C, a ≈ 0.57 °C higher in the deeper Glasgow Main mine workings than in the shallower Glasgow Upper. In the initial 2 days of the experiment, small fluctuations (<0.02 °C) were observed in the abstraction borehole. After ≈ 41 h (1.7 d) since the injection started, the abstraction temperature started to increase, reaching 0.1 °C change after 2.3 d, and a maximum of 0.51 °C at the end of the experiment, after 5 d (Fig. 7b). The injection temperature was more unstable than in the Glasgow Upper experiment due to compressor cycling of the heat pump/chiller to maintain the temperature set point. The average injection temperature was 16.8 °C, but fluctuated continuously between 15.6 and 17.5 °C.

Temperature Responses – DTS

The DTS cables were grouted into place on the outside of the borehole casing and in direct contact with mine water at the depth of the screened section. Data measured by the DTS has been plotted at the mine working depth for GGA01, GGA05, GGA07, the screened rock section above the mine working in GGA08, and at the depth of the cased off and grouted Glasgow Upper mine working in GGA02 (Fig. 8). In Glasgow Upper experiment 1, the temperature trends and relative changes for each fibre-optic cable are believed to be accurate; however, the values vary from the wellhead loggers and from the downhole hydrogeology loggers. This is partly due to the differing measurement depths and sensor positions and partly because the DTS values were fully

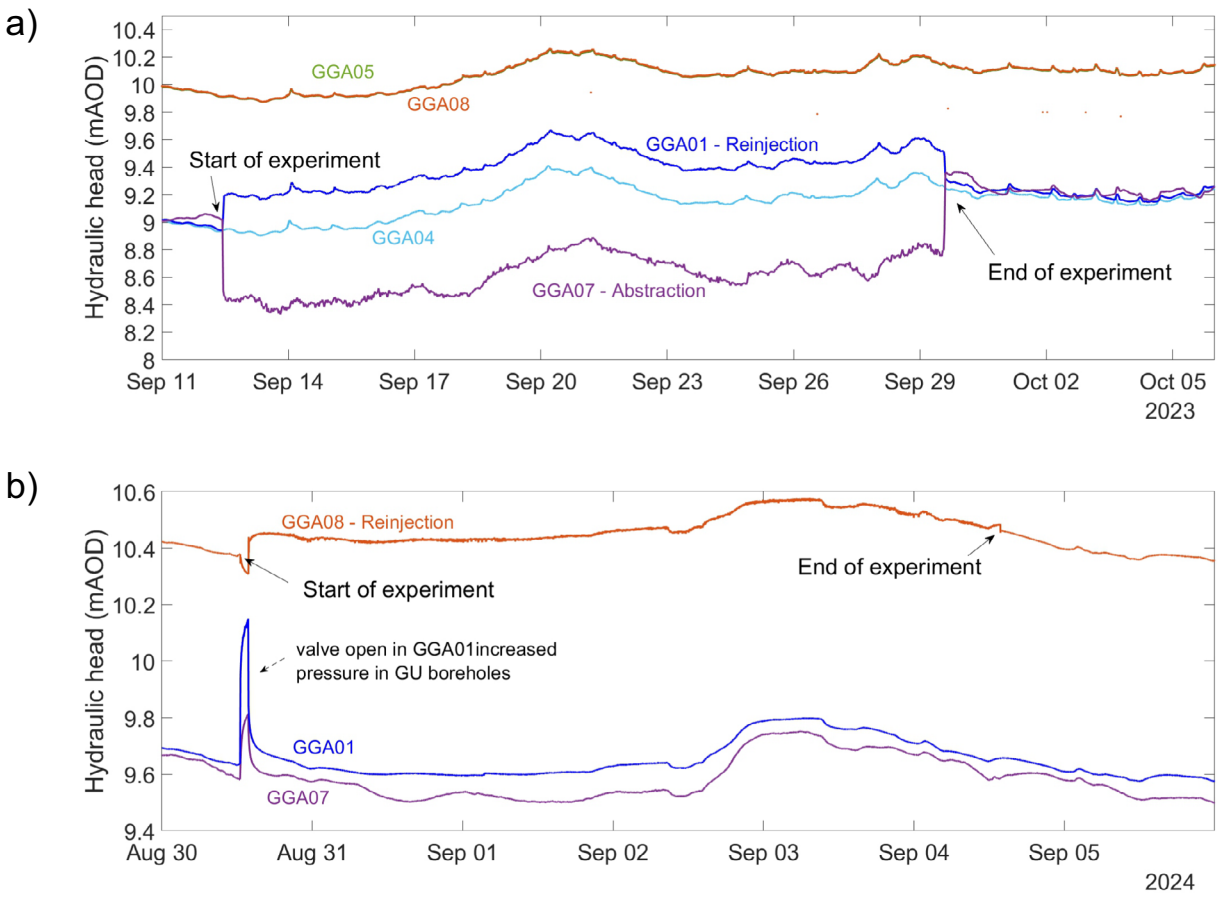


Fig. 6 Pressure responses during both experiments converted to hydraulic head (mAOD). **a** Glasgow Upper experiment **b** Glasgow Main experiment, the GGA05 downhole data logger was faulty during the Glasgow Main experiment and no responses were recorded. BGS©UKRI 2025

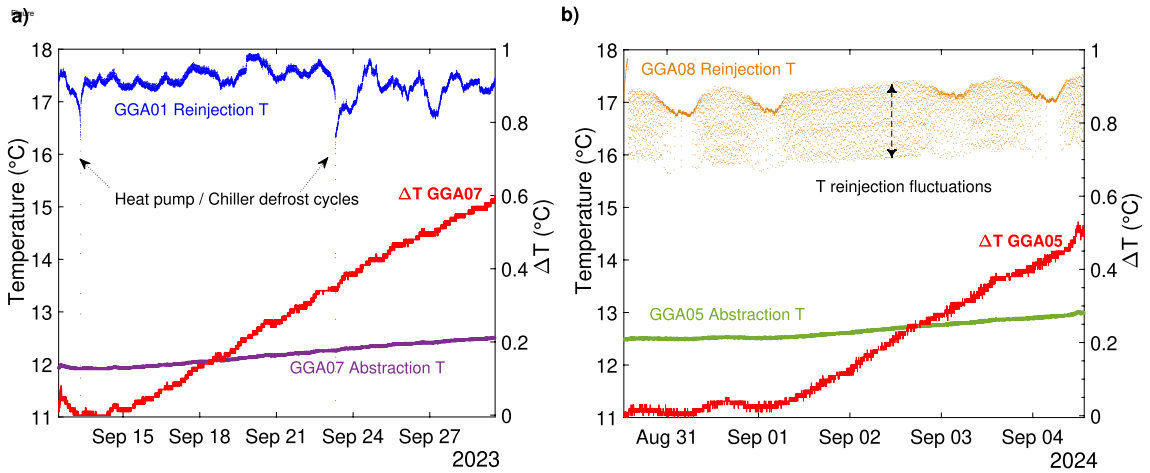


Fig. 7 Abstraction and reinjection temperatures during (**a**) the Glasgow Upper and (**b**) Glasgow Main heat injection experiments as measured at the wellhead sensors location within the flowing mine water. Experiment duration (x axis) was different. ΔT is the temperature change relative to the initial abstraction temperature in the abstraction borehole. BGS©UKRI 2025

calibrated after this experiment. For example, in GGA01, the wellhead and downhole loggers record injection temperatures of 17–17.5 °C, whereas the DTS at the mine working depth records the same pattern, but ≈ 0.2 °C cooler (Figs. 7, 8). The DTS data are more variable than the logger data and for that reason, trends have been estimated from visual changes in the slope, excluding daily spikes. The DTS variability mirrors reinjection temperature variations related to the performance of the heat pump/chiller (e.g. Gonzalez Quiros et al. 2025b), as well as artefacts from temperature variations in the surface monitoring box that are observed at all depths of the fibre-optic cable, causing 'stripes' in depth vs. time-series plots (BGS 2023b).

In the Glasgow Upper experiment 1, the temperatures recorded by DTS FO began to rise in borehole GGA02, located 10 m from the injection well, after ≈ 1.9 days

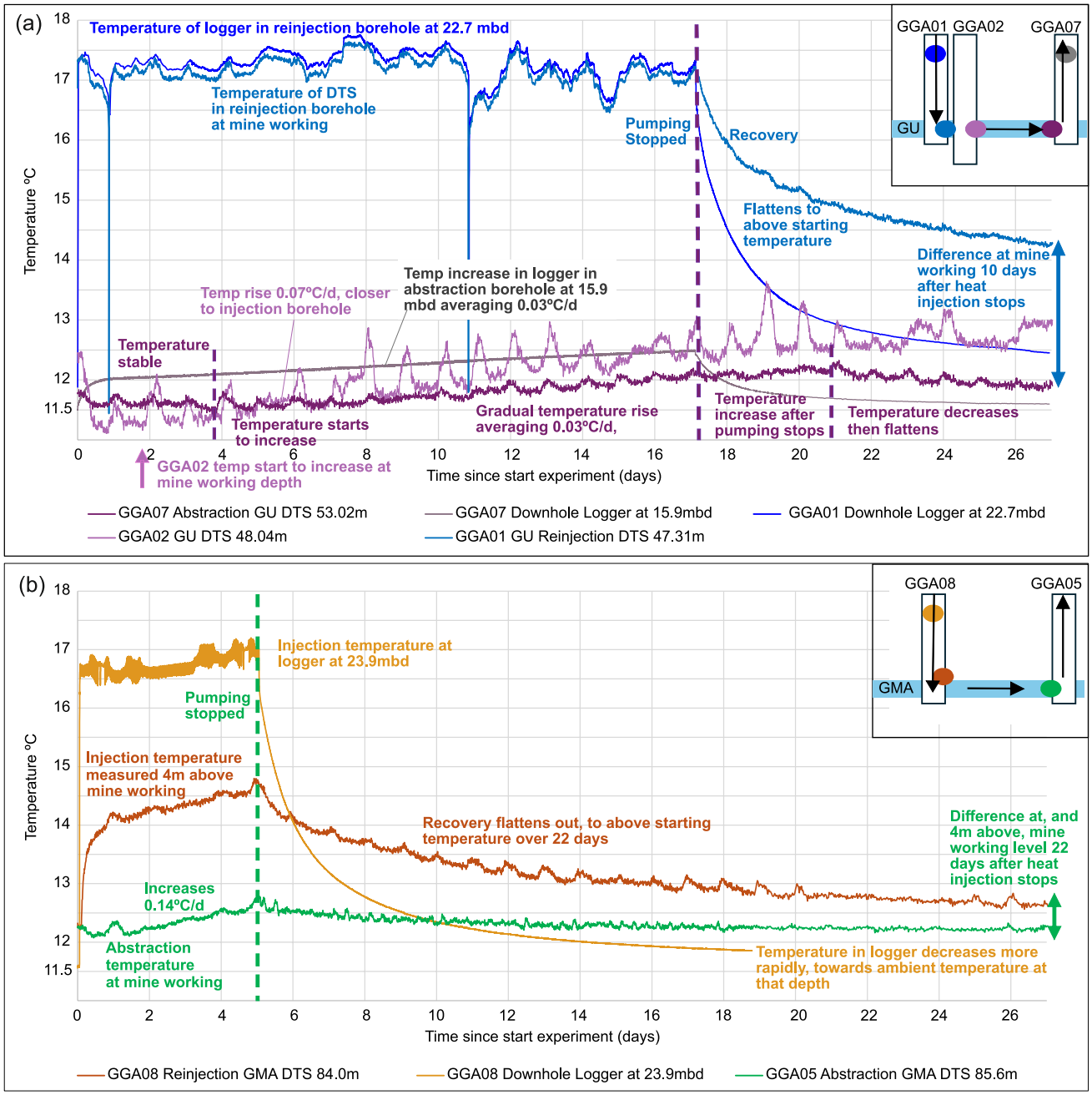


Fig. 8 Plots of single depth DTS data from mine working depth (4 m above the mine working depth in GGA08), showing the time series temperature response during (**a**) the Glasgow Upper and (**b**) Glasgow Main experiments. Both plotted from the time since the experiment started, and including recovery periods with coloured text corresponding to that sensors data. Temperature values from the hydrogeology data loggers also included. mbd= metres below datum. BGS©UKRI 2025

(Fig. 8). This is based on taking the visual trend from the lowest, flat parts of the time-series data, ignoring the approximately daily peaks. DTS temperatures measured at the mine working visually rise in the abstraction borehole GGA07 135 m away, starting at ≈ 3.9 days, showing the expansion of the thermal plume. The GGA07 wellhead and downhole loggers start to record temperature increases on similar timescales, leading to ≈ 0.1 °C of stable temperature increase at 4.8 days (Figs. 7 and 8).

In the Glasgow Main experiment 2, a gradual, stable temperature increase in the abstraction borehole 119 m away started at ≈ 1.4 days in the DTS data. The DTS temperatures measured in the reinjection borehole were between 14–14.5 °C, less than the temperatures observed at the wellhead and downhole loggers (16.5–17 °C) because the DTS terminates on the outside of a cased section of borehole, above the screened section and ≈ 4 m above the mine working, in claystone and siltstone lithologies.

In experiment 1, the parts of the experiment with a stable rate of increase of temperature varies from 0.07 °C/d in GGA02 to 0.03 °C/d in GGA07 (both from the DTS and borehole logger). The rate of temperature increase was less further away from the heat injection boreholes, as the thermal plume spreads out in the Glasgow Upper mine workings. In experiment 2, once the temperature increase started, the rate was ≈ 0.14 °C/d in GGA05 in the Glasgow Main mine workings.

Recovery Period

After the pumping was stopped at the Glasgow Upper experiment 1, the DTS data in the reinjection borehole GGA01 showed a temperature reduction of ≈ 2 °C at the mine working depth over a period of ≈ 3 days, then flattened out at a temperature > 2 °C higher than the temperature before the experiment (Fig. 8). In borehole GGA02 at the Glasgow Upper depth, the temperature continued to increase for ≈ 8 days of the recovery period and then flattened off. This may be related to a time lag because of conductive process through the grout plug in this borehole (see Gonzalez Quiros et al. 2025a). In the abstraction borehole GGA07, the temperature continues to increase by ≈ 0.15 °C for 4 days after heat injection and pumping stopped. The temperature then started to gently fall and flattened out over 6 days, returning to around the starting temperature of the experiment. Ten days after the experiment, the injection of 113 MWh thermal energy into the Glasgow Upper mine working produced a temperature differential between the injection and abstraction boreholes of ≈ 2.3 °C.

With a shorter experiment, less heat energy (26 MWh) was injected into the Glasgow Main mine workings over 5 days. Though the DTS is not in direct contact with the mine water in the working, the pattern of recovery in GGA08 is similar, with an initial rapid decrease in temperature, flattening out over 10–20 days. In the abstraction borehole GGA05, the temperature in the mine working gradually fell by ≈ 0.3 °C over 14.5 days and then remained at ≈ 12.2 °C for 7.5 days. 22 days after the experiment ended, the injection of 26 MWh thermal energy into the Glasgow Main mine working produced a temperature differential between injection and abstraction boreholes of ≈ 0.4 °C.

Integration and Summary of Experimental Results

The pressure responses during both experiments confirm the high transmissivity of the mine workings (around the operational boreholes), and the good intra-seam connectivity (i.e. between boreholes screened in the same mine workings). On the other hand, inter-seam connectivity is limited, as confirmed by the negligible pressure response in the boreholes intersecting non-tested mine workings.

In the Glasgow Upper, pressure changes from the same flow rate (either pumped or injected) were larger in GGA07 than in GGA01 (with opposite sign). This slightly lower borehole productivity in GGA07 could be explained by construction and near-borehole effects (such as a lower flowing surface due to the existence of a coal pillar) or to the hydraulic properties and connectivity in the mine workings near the borehole. Lower pressure changes in GGA01, screened into waste, would indicate more facility for water to flow between the borehole and to and into the mine workings.

In the Glasgow Main experiment, there is only data available from the reinjection borehole (GGA08). For the same flow rate as in the Glasgow Upper experiment, the pressure changes in this borehole were lower, indicating a very high injectivity for this borehole, even though it only partially penetrates the mine working void in a zone of very high transmissivity (Fig. 6).

The arrival time of the thermal breakthrough of 0.1 °C was interpreted in the Glasgow Upper after 4.8 days and in the Glasgow Main after 2.3 days, using the well head temperature sensors. The thermal breakthrough in both cases was small and gradual, as opposed to a single pulse of water 5 °C hotter than the starting temperature. The rate of temperature increase was greater in the Glasgow Main abstraction borehole (0.14 °C/day) than in the Glasgow Upper abstraction borehole (0.03 °C/day), for similar flow rates and ΔT applied across the borehole doublets (Fig. 7).

The longer thermal breakthrough time in the Glasgow Upper mine workings aligns with the interpretation of a greater percentage of backfilled mine workings and abstraction-injection boreholes located transverse to the direction of former coal pillars, likely creating a longer and wider flow path. In contrast, the Glasgow Main mine workings

is interpreted to have been more widely worked by 'total extraction' and may have a greater percentage of roadways and open voids remaining today, as shown by GGA05 and GGA08 and indicated by the higher transmissivity of ≈ 2100 m^2/day estimated by Shorter et al. (2021).

In addition to the mine heterogeneity, borehole spacing is likely to influence thermal breakthrough times and heat transport processes. The Glasgow Main abstraction and reinjection boreholes are 0.9 times the distance of the Glasgow Upper boreholes (119 m vs. 135 m). However, the Glasgow Main experiment thermal breakthrough time is 2.1 times as fast (56 h vs. 116 h) and the rate of temperature increase in the abstraction borehole is 4.7 times as large (≈ 0.14 °C/d vs. ≈ 0.03 °C/d), implying that the borehole spacing is a minor part of the measured response.

The heat (thermal power) injected into the mine workings supplied by the heat pump/chiller and heat exchanger operations varied somewhat through both experiments, with an average value of 274 kW_{th} for Glasgow Upper experiment and 215 kW_{th} for Glasgow Main experiment. The response at the abstraction boreholes was similar (an initial stable period followed by a gradual rise in temperature up to ≈ 0.5 or 0.6 °C, Fig. 7), even though the duration of the Glasgow Main experiment was much less (121.8 h vs. 411 h).

The cumulative amount of heat energy injected into the mine workings was 113 MWh in the Glasgow Upper experiment and 26 MWh in the Glasgow Main (calculation in supplemental file S-14). The calculated energy recovered at the abstraction borehole in each experiment was ≈ 5.4 MWh in the Glasgow Upper vs. ≈ 0.98 MWh for the Glasgow Main experiment. However, both experiments had different durations, and therefore the cumulated values are influenced by the total time. For comparison, we estimated the recovered heat energy for an equivalent duration of 121.8 h (the duration of the Glasgow Main experiment) for the Glasgow Upper. In that period, the total injected heat in the Glasgow Upper was ≈ 33 MWh and the recovered heat in GGA07 was 0.185 MWh, resulting from a combination of later thermal breakthrough and a less steep temperature increase. That is, ≈ 6.7 times more heat energy was recovered from the Glasgow Main experiment for an equivalent duration, even though 1.3 times more thermal energy was injected during the Glasgow Upper experiment.

Discussion

Insights from Mine Characterisation

By combining the exceptional level of borehole, abandonment plan, and hydrogeological testing data available for characterisation of the mine workings utilised by the UK Geoenergy Observatory with knowledge acquired from visits to coal mine workings formerly exposed in analogous Scottish opencast coal sites, we illustrate and extrapolate the variability of mine water reservoir types in workings ≈ 100 years old (Figs. 2, 3, 4, and 5, and Table 1). Since these opencast coal sites are no longer active, and as the knowledge of former deep miners in Scotland is lost, the images, photographs may assist investigators and modellers of other potential mine water geothermal sites in understanding or predicting mine water reservoir character and fill types that influence flow and heat transport.

Key transferable observations on the mine water reservoir include that the type (pillar and stall, total extraction, backfill, goaf, open void, etc.) varies over metres to tens of metres. As highlighted by others (e.g. Andrews et al. 2020; Guo et al. 2018; Mason et al. 2019), fracturing above and below the mine workings increases the volume of the mine water reservoir. At this site, the boreholes proved more intact or partially intact coal pillars in the Glasgow Upper than was expected based on the mine abandonment plan (Monaghan et al. 2022), with the implication that with support left in place, the mine working has more open voids than expected. This is contrary to verbal knowledge sharing from ex-mine surveyors that 'pillar robbing' and mining of more coal than shown on the abandonment plan was common.

Influence on Flow and Heat Transport and Storage

The combination of mine characterisation with the data from the two heat injection experiments has allowed for a new understanding on the influence of the mine workings properties and geometry on groundwater flow and heat transport, with implications for geothermal operations.

As the thermal plume spread out in the mine workings during the heat injection experiments, both the rate of temperature increase and the magnitude of temperature change decreased with distance from the reinjection borehole (e.g. Glasgow Upper experiment, GGA02 vs. GGA07). This is attributed to the combination of thermal dispersion and heat transfer between water and rock within the mine water reservoir (Fig. 9). However, the evolution of the abstraction temperature and rates of temperature change in the abstraction borehole differ in the two experiments, even when the flow rates and distances were similar, which is attributed to the influence of mine geometry, distribution and characteristics of the mine workings, and the complex interactions with the mine working fill type and the surrounding rock.

Experiment 1 using the Glasgow Upper mine workings resulted in different, opposite changes in pressures responses to abstraction and reinjection, with larger changes in abstraction borehole GGA07. This is consistent with previous observations (Shorter et al. 2021) that assigned

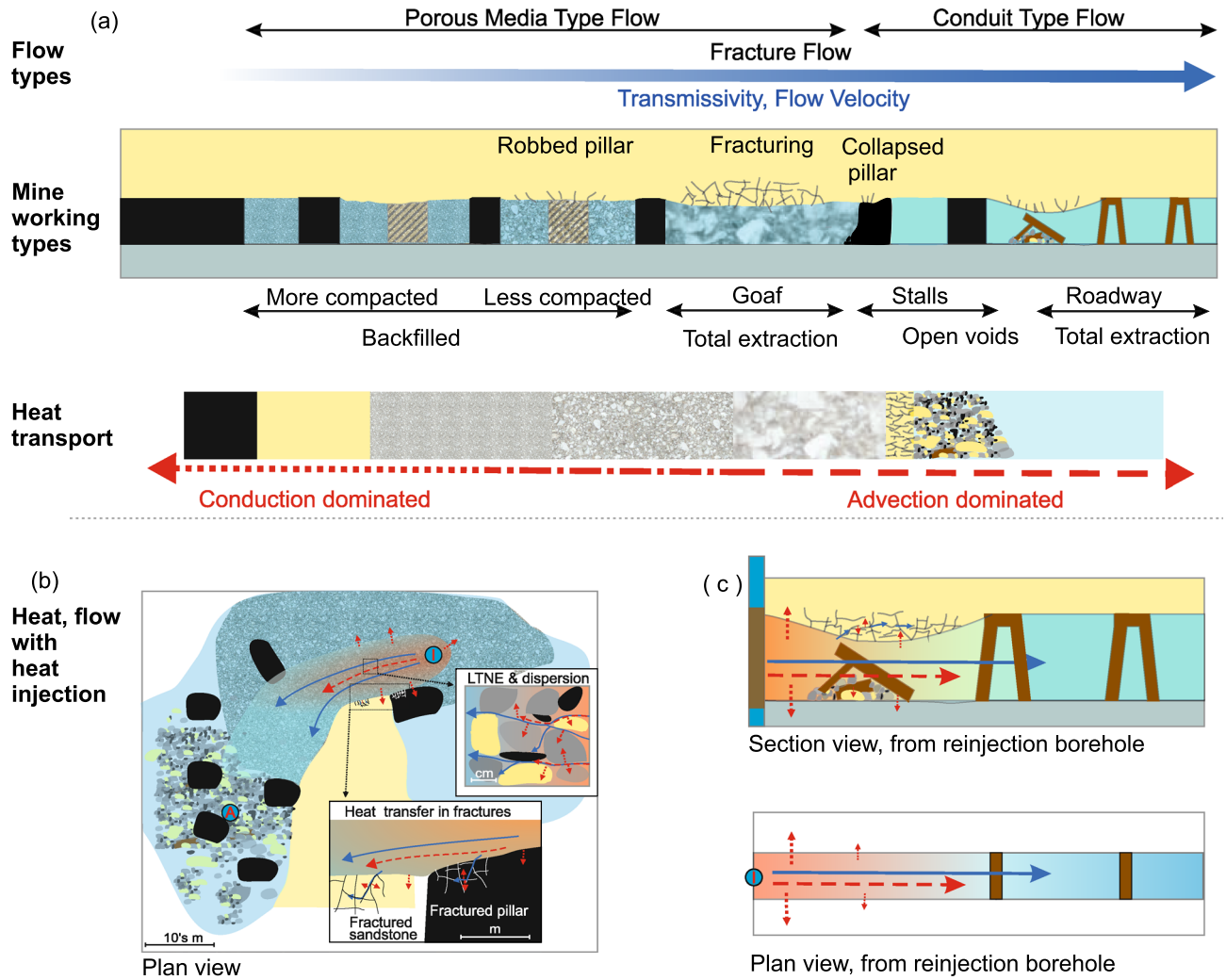


Fig. 9 Synthesis of mine working types, flow and heat transport processes. Rock type colours as Fig. 4. **a** visual summary of mine working types, flow and heat transport processes **b** plan view of heat transport processes interpreted in different types of mine working. LTNE= local thermal non equilibrium effects, A=abstraction borehole, I= reinjection borehole. **c** simplified view of heat transport processes to rock surrounding the mine working. BGS©UKRI 2025

slightly lower transmissivity to this borehole and the surrounding area than to the reinjection borehole GGA01, from drawdown data. The mine workings is interpreted to be filled with ≈ 60% of loosely packed waste, coal pillars, and former roadways near GGA01 and GGA02 (Table 2); the waste forms a transmissive material with characteristics of porous media and there are possibly fewer boundaries to radial flow (inset Fig. 9b). At the Glasgow Observatory, the Glasgow Upper mine working has high transmissivity (950–1020 m^2/d, Shorter et al. 2021) with much evidence of loosely packed waste, contrasting with Gillett's (2024) low permeability measurements (<0.01 mD) of clay-rich waste within pillar and stall workings exposed in north-east England. In the modelling studies of Li et al. (2020) and Wang et al. (2025) backfilled, goaf, and fractured zones considered as geothermal and MTES targets have variability dependent on roof rock strength, lithology and thermal conductivity of the backfill, highlighting the range of known types and fill properties within waste and goaf.

Though highly transmissive and connected systems through the pressure response, the flow path from the reinjection borehole (GGA01) to the abstraction borehole (GGA07) is likely to be tortuous and provide large surface area for heat transport. Heat transport is preferentially dominated by advection in the mine workings during the abstraction and reinjection period, but heat conduction has been shown to play an important role with control by thermal properties of the surrounding rocks (Receveur et al. 2026b).

There is also evidence for fracturing above and below the Glasgow Upper mine working, further increasing the volume of the reservoir and the complexity and length

of the flow paths (Fig. 9b). Electrical resistivity imaging has been interpreted to indicate that the volume of influence of the thermal plume following a 'cool' injection at the Observatory was not limited to the mine workings but extended several metres above and below (Gonzalez-Quiros et al. 2024). This increases the total surface area for heat transfer between the circulating water and the rock and has implications for geothermal exploitation and thermal energy storage (Heinze and Gunatilake 2025).

Where the mine water reservoir is filled by waste and goaf, the pieces and fragments of rock have a high surface area and are likely to create diffuse pathways, with greater potential for conduction into the fill. This is likely having the effect of slowing the rate of increase of temperature via heat loss as the thermal plume spreads. The character of the waste and goaf is important. Loosely packed backfilled waste (stowage) may keep a mine working open with high transmissivity, whereas tightly packed, compacted clay-rich backfilled waste may result from collapse of the working. Goaf from a roof collapse may comprise large, angular rock pieces and increase the thickness of the mine water reservoir. A detailed description and quantification of the heat transfer between the water and the rock during the injection, storage, and recovery periods is a key challenge due to the variability of materials and scales. The thermal properties of the backfilled and goaf zones would be a combination of the thermal properties of the rocks (heterogeneous composition) and the fraction of voids. The degree of compaction in the backfill and resultant porosity change, would change the thermal properties.

In the Glasgow Main experiment 2, the higher transmissivity of the mine workings (1976–2100 m^2/d in Shorter et al. 2021) resulted in much lower pressure changes than in the Glasgow Upper experiment at the same flow rate. This is consistent with the characterisation pumping tests (Shorter et al. 2021). In the Glasgow Main mine workings, the higher transmissivity and borehole evidence of open voids leads to an interpretation of a higher percentage of former roadways and voids remaining open. These will act as preferential flow and heat transport pathways for the thermal plume during pumping, leading to the observed higher rate of temperature increase. The flow and heat energy are interpreted to be focussed on these high flow 'pipes' with less surface area for heat transport through conduction to the rock mass, and quicker transit time to the abstraction borehole, as recorded by the observed thermal breakthrough (Fig. 9a and c).

The transition between porous media and conduit type flow cannot be clearly defined from the mine plans, since that level of detail is not recorded and changes may have occurred since abandonment. Another uncertainty on heat transport between the water and rock is if higher flow rates, with increasing flow velocities, can lead to turbulent flow.

Fracturing of the bedrock or the coal pillars would change the original properties of the rock and, as a result, affect the flow in these mine water reservoir types. The effect of faults, which can act as either flow barriers or preferential pathways is uncertain, and likely to vary dependent on lithology and faulting style (Ó Dochartaigh et al. 2015).

In some of the mine water reservoir types (Table 2), such as backfilled zones with rock pieces, goaf, or fractured zones, an assumption of local thermal equilibrium (LTE) might be inappropriate. That is, heat transfer between water and rock is not instantaneous, as is assumed with equivalent thermal property and temperature changes between phases. It has been shown (e.g. Gossler et al. 2020) that local thermal non-equilibrium effects mainly impact the effective thermal dispersion, increasing its value with higher velocities and larger particle sizes. These authors have shown that in gravel aquifers in which flow velocities are of various meters per day, local thermal non-equilibrium effects are expected. Greater thermal dispersion leads to a larger spreading of the thermal plume. Such effects would support the interpretation of the attenuated signal observed in Glasgow Upper experiment 1 and would have implications on the storage volume (i.e. a wider spreading of the thermal plume would mean lower energy density in the reservoir) and the rates of heat storage and recovery, resulting in various superimposing rates of heat transfer at different temporal scales. A detailed analysis with implicit heat transfer between phases (Heinze 2024) would be an appropriate approach, but its application is challenging.

Implications for Mine Water Geothermal and Thermal Energy Storage

Predicting and Understanding Responses in Complex Mine Workings – Implications for Borehole Siting

For other mine water heat projects, can the results of this work be used to inform desk studies of legacy data, to predict the character of the mine water reservoir to be drilled into and its hydrogeological properties? Excepting targeted drilling into mine voids, which Wyatt et al. (2025) document for GB as 68% hit void space, the variability in the mine water reservoir type over a few metres leads to challenges in prediction at specific borehole sites. However, the results of this study suggest that factoring in local understanding from mining records or legacy boreholes on stowage/waste and roof collapse, as well as the trend of extracted panels/pillars,

can usefully inform exploration borehole siting and prediction of hydrogeological response to a geothermal doublet.

Analysis of characterisation pumping tests can provide invaluable information about borehole productivity and system transmissivity, as pressure responds very quickly to features in the mine water reservoir, including near-borehole effects, the flow regime, and other important features such as non-permeable boundaries (e.g. Ferroud et al. 2019).

The results also show the importance of the connectivity of the borehole to the wider mine working properties for thermal plume development and processes, as well as the borehole transmissivity. Since drilling and testing of boreholes requires high capital expenditure and is a commonly cited barrier to wider deployment, understanding that the connectivity to, and properties of, wider mine workings could enable a range of heat or MTES options, could provide some flexibility in borehole siting, and reduce drilling risk.

Detecting, Monitoring and Characterising Thermal Plumes

In experiment 1, ≈ 113 MWh of heat was injected into the Glasgow Upper mine working at a 12 L/s pumping rate (Table 1) with a response of 0.1 °C change at the abstraction borehole in 4.8 days. In a heat abstraction experiment using the same boreholes (GGA01, GGA07; Glasgow Upper mine working) and lower flow rate of 6 L/s, a similar 0.1 °C cooling response was detected over a longer time period (10 days, Gonzalez Quiros et al. 2025a). In addition, the thermal breakthrough in the heat injection experiments (this study) was much clearer, increasing at a stable rate to 0.59 °C after 17 days. Clearly, the flow rate and the injection of 'cool' vs. heat have a measurable influence on the thermal responses that is not yet fully understood. It remains to be tested whether temperatures would keep on rising at a stable rate with a longer duration of heat injection, or whether they would start to rise more quickly or reach a constant temperature plateau.

Outside of a mine water research observatory, there is likely to be less extensive and less precise monitoring. Most commonly, monitoring may be via a downhole logger located some distance above the mine working, rather than via DTS or an 'in-the-flow' sensor at the wellhead. This work has shown that variations of 0.1 °C observed using downhole loggers on similar timescale and magnitude to the other sensors, and therefore can be used to monitor thermal breakthrough. Outside of the pumping periods, there are notable differences between the downhole hydrogeological logger temperature values and rates of change than at the depth of the mine working interval. For example, the ambient temperature is lower due to the shallower position of the downhole logger in the borehole, and the recovery to ambient temperature is quicker than at the mine working.

Sustainability and Management of Geothermal Resources

If considering thermal responses and sustainable heat abstraction within the same mine working, the results of the two experiments provide useful data on thermal breakthroughs, beginning with timescales of days for high transmissivity and laterally connected mine workings during active pumping. This supports the 'rule of thumb' guideline that abstraction-reinjection flow paths should be as long as possible. There are clear implications for locating multiple mine water schemes within an interconnected single working within a few hundred metres of each other. This work provides data to quantify approaches for regulation and licensing, such as proposed by Sweeney et al. (2025) for multiple systems in close co-location.

In contrast, some of the observed characteristics, such as the connectivity of a single mine working and dispersion of heat, may have implications, some advantageous, for the management of mine thermal energy storage (MTES). The heat injection experiments described in this paper would represent only a part of operation of an MTES system. Future work could investigate heat recovery with abstraction following heat injection at various flow rates or cycle times, to better quantify recovery efficiency and the contribution of storage in water in open voids, in bedrock via conduction, etc. However, the different rates of increase and recovery of temperature observed in the two mine workings suggest that the type of mine workings are a key factor to inform design and management decisions for optimised application of MTES, especially regarding their operational timescales (storage cycles) from shorter (daily to weekly), to longer cycles (weeks to interseasonal) of operation.

Numerical Modelling and Future Work

Accurate numerical modelling of mine water systems is complex due to the combination of various factors: geometry, uncertainty in zonation of mine water reservoir types, assignation of flow laws (conduits vs. porous type), properties, and boundary conditions. Predictive numerical modelling of mine water geothermal systems, especially in the absence of data, relies heavily on the analysis and digitisation of mine workings plans (Gonzalez Quiros and Fernandez-Alvarez 2019; Mouli-Castillo et al. 2024), as well as on physical laws with their respective boundary, exchange, and coupling conditions. As highlighted in this work, mine plans can be used to provide an initial characterisation of the mine reservoir and help in the definition of the flow domains, but always with some degree of uncertainty, especially for old

poorly documented mines and where post-abandonment changes are likely to have taken place.

Numerical modelling of the thermal plumes developed during the heat injection experiments was attempted using FEFLOW (Gonzalez Quiros et al. 2025b) with zonation of the mine workings under the assumption of Darcian flow in an equivalent porous media. Whilst calibration with hydraulic heads from GGA01, GGA04, and GGA07 produced a very good fit and the heat transport modelling of the thermal plume arrival gave a reasonable approximation of the thermal breakthrough time using the parameterisation of the mine working heterogeneity described above, inaccurate values of the magnitude of temperature change were obtained. Several factors, such as heat transfer into the rock mass enhanced by fracturing, some details missing in the (uncertain) distribution of mine workings, or local thermal non-equilibrium (LTNE) effects (Gossler et al. 2020) could explain these errors. Further laboratory and field experiments and more detailed numerical models, both geometrically and physically, are required to evaluate these effects and how they likely affected the observations.

However, large-scale operational numerical models that consider all of the physics and detailed geometry would be computationally expensive. It has been shown (Receveur et al. 2026a) that as the simulation time increases, heterogeneities play a smaller role on the estimation of heat extraction. Therefore, for some applications, the use of appropriate simplified models provide reasonable results at a fraction of the computational cost. Further analysis and investigations are required, outside the scope of this paper, to evaluate the spatial and temporal scales of application of the properties and processes under consideration, that must be adapted to the site-specific hydrogeological characteristics, mine geometries, and operational settings.

Conclusions

Two heat injection experiments performed at the UK Geoenergy Observatory in Glasgow have revealed the geometry and type of mine workings influence the heat transport processes. Both experiments were conducted under very similar conditions, but thermal breakthrough times were more than twice as long in the Glasgow Upper mine workings, apparently due to a greater percentage of backfilled mine workings and a likely more tortuous pathway between the borehole doublet. Temperature increase in the abstraction borehole was also more gradual at ≈ 0.03 °C/day from 3.9 days after the experiment started (Glasgow Upper mine working), compared to 0.14 °C/d from 1.4 days after the Glasgow Main experiment start, where the borehole doublet was in a mine working interpreted to have greater percentage of open voids and higher transmissivity. As a result, ≈ 6.7 times more thermal energy was recovered from the Glasgow Main experiment than the Glasgow Upper during an equivalent 121.8 h period.

The results demonstrate that the complexity mine water reservoir types and geometries influence the processes of heat transport, which in turn influences system performance for geothermal or MTES exploitation. The improved understanding of thermal processes and rates has implication for the long-term sustainability and heat potential of flooded mines:

- For mine water geothermal heat abstraction, the data provide quantification for the ‘rule of thumb’ that abstraction-reinjection flow paths should be as long as possible, since the short ‘intra-seam’ flow paths in these experiments highlight temperatures start to change with thermal breakthrough on timescales of days. The evidence indicates that mine water heat abstraction projects hundreds of metres apart in the same, well connected mine working may not be sustainable long-term. The data informs regulation and permitting approaches, planning and siting of drilling locations, and reinforces the approach generally taken that co-located heat abstraction and reinjection boreholes are screened in different levels of mine working.
- For thermal energy storage, these experiments provide insights on the dominant conductive and advective heat transfer processes and their timescales, such as the differences between mine workings with more backfilled waste, goaf and collapse compared to those connected by former roadways and open voids and with higher transmissivity. This variability would have different implications for the operation of MTES and optimisation of daily, weekly, or interseasonal cycles of operation.

The results add to the growing literature quantifying heat transport processes at-scale, in real world settings. However, there remains uncertainty about parameter distribution and the magnitude and scale of the thermal processes that requires further research and experimentation. For example, longer experimental runs, more comprehensive analysis of recovery, and push–pull tests under various cycle lengths are needed in future studies.

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Data Availability The raw data files for the hydrogeology logger, wellhead and DTS sensors used in this paper (Figs. 6, 7, 8) can be found in supplementary information files S-1–S-13. The recovery data includes some open access data collected as part of environmental monitoring, outside of the period the UK Geoenergy Observatory was specifically used for the GEMS experiments.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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