

Characterizing the thermal state and recovery potential of flooded coal mines using fibre optic Distributed Temperature Sensing methods

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ABSTRACT

Mine water geothermal and thermal energy storage offers opportunities to contribute to the decarbonisation of heating, taking advantage of the large volume of water stored in mining voids over extensive areas. Tens of successful mine water heat recovery schemes are currently operating worldwide. However, their widespread development is hindered by the uncertainties in assessing the resource potential and system sustainability. In Glasgow, United Kingdom, the UK Geoenergy Observatory (UKGEOS) has been developed to provide an at-scale research facility to study mine water geothermal energy. The facility includes five mine water boreholes accessing the flooded mine workings of the Farme Colliery, closed in the 1930s, all equipped with Distributed Temperature Sensing (DTS) fibre optic cables, that allows the continuous monitoring of temperature, and provide insights into hydrogeological and thermal processes within the flooded galleries and surrounding rock mass. This paper presents the results of six months of DTS monitoring in two mine water boreholes. Data analysis is used to characterize the thermal state of mines, including the effect of the reservoir properties and heterogeneities, the fluctuations linked to natural processes and in response to heat injection-abstraction experiments. This large-scale analysis provides insights into the overall long-term heat and storage potential of mines, and to the optimal design of these systems across the world.

1. INTRODUCTION

Flooded mine workings are a source of low-grade geothermal heat that can be harnessed using ground source heat pump (GSHP) systems. Heating accounts for around one third of the greenhouse gas emissions in the UK, where most of the heat used for water and space heating is sourced from natural gas (UK POST, 2016). In the UK, about 8% of the population in England, 10% in Scotland and 25% in Wales lives in former coalfields

(Beatty et al., 2007) and could directly benefit from the underlying low carbon, mine water heat resource.

Despite of the large volume of 12-20°C water available in mine workings, the widespread development of mine water geothermal in the UK is partly hindered by various social and technical factors, including the limited understanding of the long-term behaviour and sustainability of heat abstraction from these systems (Farr and Busby, 2020).

Mines consist of an interconnected network of galleries, workings and shafts, with open voids, fractured zones, compacted material and undisturbed rock mass that may involve multiple thermal and hydraulic processes (free and forced convection, turbulent flow, fracture/pipe flow, heat conduction). Alongside this structural complexity, unknowns on the extent of post-closure subsidence and roof collapse and the lack of in-situ temperature and flow data make it difficult to characterise the thermal state of mines and the extent of the thermal disturbances (e.g. thermal breakthrough) caused by geothermal operations through numerical approaches (Farr et al., 2021; Gonzalez Quiros et al., 2024).

The UK Geoenergy Observatory (UKGEOS) in Glasgow, Scotland, provides a unique opportunity to study mine-water geothermal and mine thermal energy storage (MTES) (Monaghan et al. 2022). The research facility accesses two flooded levels of worked coal seams in the Farme colliery, closed in the 1930s. Various monitoring instruments are deployed at the surface, in the boreholes and the heat centre to provide a continuous record of water temperature, pressure, chemistry and electrical conductivity at multiple locations across the Observatory. The six boreholes drilled down to the depth of mine workings are also equipped with fibre optics for Distributed Temperature Sensing (DTS) and with cables for Electrical Resistivity Tomography (Monaghan et al., 2022).

This paper summarises the observations and learnings from continuous DTS acquired in two of the five mine-water boreholes between September 2024 and March 2025. DTS is used to provide insights into the temporal

and spatial temperature changes occurring in the mine and overlying rock mass at the scale of the Observatory, with an unprecedented level of detail in Carboniferous strata in the UK. Results are used to characterise the thermal state, structure and behaviour of mine water systems under natural conditions and after short-term geothermal tests and understand the capabilities of DTS to inform on the subsurface potential for geothermal energy or mine thermal energy storage.

2. THE GLAGOW OBSERVATORY

2.1 Site description

The UKGEOS Observatory in Glasgow, which started geothermal operation in 2023, consists of twelve boreholes and a heat centre along multiple monitoring capabilities. Five of the boreholes were drilled down, and screened across two of the seven coal seams mined in the Farme colliery, the Glasgow Upper (GU) and Glasgow Main (GMA). Five environmental baseline monitoring boreholes were drilled into the bedrock above the GU or in superficial deposits; and one fully cased sensor testing borehole, GGA02, was drilled to a depth of c. 94 m across the shallower coal seams (Monaghan et al., 2022). Downhole loggers, installed in the Observatory boreholes provide a continuous record of the pressure, conductivity, salinity and temperature within the boreholes.

Three of the sites are connected to a heat centre equipped with 3 heat exchangers, and a heat pump-chiller infrastructure (Figure 1). Among the mine water boreholes distributed in the three clusters, two of them (GGA05 and GGA07) are equipped with a submersible pump, and four boreholes (GGA01, GGA05, GGA07 and GGA08) with a reinjection main, which allows multiple combinations of heat injection-abstraction experiments for the study of flow and heat transfer across the mine workings. As the Observatory is used for research purpose only, experiments can be conducted with more flexibility than in an operational system connected to a user with heat demand.

Table 1: List of mine water boreholes at the UKGEOS Observatory, Glasgow. GU: Glasgow Upper, GMA: Glasgow Main.

Site	Borehole	Drilled depth (m)	Mine working
1	GGA01	52.00	GU
	GGA02	94.16	GMA (no screen)
2	GGA04	53.63	GU
	GGA05	88.5	GMA
3	GGA07	56.9	GU
	GGA08	91.37	GMA

Site 2 and Site 3, of interest for this work, consists of the mine water boreholes GGA04 and GGA05; and GGA07 and GGA08, respectively (Table 1).

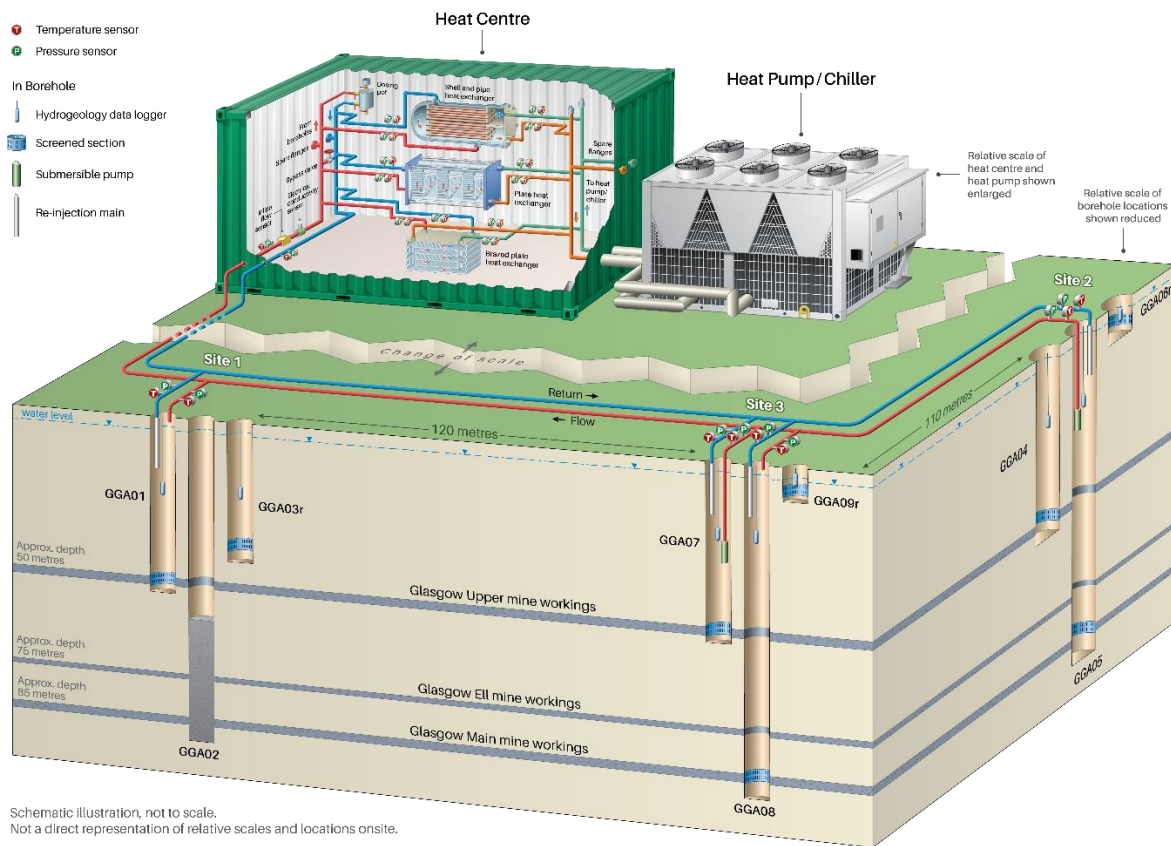


Figure 1. Infrastructure of the UKGEOS Observatory, showing the location of the mine water and environmental monitoring boreholes, and the surface installation BGS@UKRI.

2.2 Distributed Temperature Sensing

DTS is a method that uses fibre optic (FO) cables to produce a continuous profile of in-situ temperature. The method has been used to infer hydrogeological and geothermal properties of the subsurface and study the flow pattern from naturally occurring thermal anomalies (e.g. Read et al., 2014; Simon et al., 2021). In passive mode, a DTS interrogator box connected to the top of the FO cable generates a pulsed laser signal that propagates through the cable. The cable records temperature-dependent backscattered signals that are then converted into temperature values at discrete sections along the fibre (McDaniel et al., 2018).

At the Glasgow Observatory, all mine water boreholes are equipped with DTS FO cables, installed at the outside of the 11” (280 mm OD) Boode Well casing. These have been delivering DTS information quasi-continuously via two DTS boxes connected at two of the three sites at the time since May 2023. The DTS FO cables record with a high temporal and spatial resolution (every 10 or 30 min at a 25 cm resolution) the temperature along the boreholes, including any thermal response induced by heat injection/abstraction. The annular space was grouted after the installation except in the screened intervals (Monaghan et al., 2022) at the depth of one of the two mine workings (Table 1), this being the only section where the DTS FO cables are in direct contact with circulating mine water. Outside the screen interval, DTS records the response to heat conduction through the borehole walls (casings and grout) and reservoir rock.

2.3. Data analysis and selection

This paper presents DTS data in various formats recorded in GGA05 and GGA08, screened at the Glasgow Main, between the 18th September 2024 and the 4th March 2025 (Table 2).

Table 2: DTS acquisition and experiments conducted at UKGEOS Glasgow between the 18th September 2024 and the 4th March 2025 indicating the sampling resolution for each time interval.

	18/09/2024	13/01/2025	04/02/2025	04/03/2025
GGA04	30 min	10 min	30 min	
GGA05	30 min	10 min	30 min	
GGA07	30 min	10 min	30 min	
GGA08	30 min	10 min	30 min	
EXPERIMENTS		stepped test		

The best borehole and time interval for the analysis of the most representative register of undisturbed temperature was selected based on these criteria:

- The borehole accesses the deepest, Glasgow Main, mine working (deep profiles).
- The borehole was involved in the least number of heat injection-abstraction tests, minimizing the potential thermal disturbances.

- Continuous DTS acquisition was performed at both sites where the boxes are installed during the period of analysis.

The selected study period coincides with the longest continuous DTS monitoring available at sites 2 and 3. It includes periods without operation that show temperature changes responding to natural processes and recovery periods after a series of short-term tests (i.e. up to 6 h) that used various borehole combinations with GGA05 or GGA07 as mine water abstraction boreholes and GGA08 as a mine water injection borehole (Table 3). A longer test was conducted between the 13th and 16th January 2025 (Table 1) in the form of stepped heat injection and abstraction involving GGA07 and GGA08. Although the thermal response to heat injection-abstraction experiments is beyond the scope of this study, accounting for tests occurring during the period of analysis is essential to understand the potential disturbances on the baseline temperature. Short-term tests are assumed to cause negligible disturbances of the rock mass temperature, with the DTS signal over short periods being most likely the response to heat transfer within the borehole walls.

Table 3: Heat injection-abstraction tests conducted during the study period. The glycol loop mode includes cooling (C - heat abstraction test) or heating (H - heat injection test)

Test	Combined Duration (HH:MM)	Glycol Loop Mode	Flow rate	Injector	Abstractor
4/10/2024	00:47	N/A	12	GGA08	GGA05
11/10/2024	01:13	C?	12	GGA08	GGA05
29/10/2024	00:35	N/A	12	GGA08	GGA05
31/10/2024	00:39	C	12	GGA08	GGA05
07/11/2024	03:14	C	12	GGA08	GGA05
14/11/2024	05:36	C	12	GGA08	GGA05
3-4/12/2024	06:50	N/A - C	3,6,12	GGA08	GGA05
8/01/2025	00:52	C	12	GGA08	GGA07
13/01/2025	03:18	C	3	GGA08	GGA07
14/01/2025	05:47	C	6,9	GGA08	GGA07
14/01/2025	01:47	C	9	GGA08	GGA05
15/01/2025	03:33	C	12	GGA08	GGA07
15/01/2025	02:26	H	3	GGA08	GGA07
15/01/2025	01:28	H	9	GGA08	GGA05
16/01/2025	06:45	H	6,9,12	GGA08	GGA07
16/01/2025	01:03	C	12	GGA08	GGA07
23/01/2025	00:50	N/A	12	GGA08	GGA05
27/02/2025	00:33	H	12	GGA08	GGA07

3. RESULTS

3.1. Depth Temperature Response

Figure 2 shows the temperature change along GGA05 as a continuous time-depth DTS signal between the 18th September 2024 and the 4th March 2025, alongside the geological log displayed on the left. The DTS profile terminates at 88.2 m, just below the Glasgow Main encountered between 84.7 m and 85.4 m (Barron et al., 2020). The DTS timeseries at 0.9 m during the period of analysis is also presented alongside the air temperature measured at the UKGEOS Observatory Glasgow weather station.

The DTS time-depth profile in GGA05 showed a relatively uniform background temperature of c. 11-12°C, that slightly increased with depth. Vertical stripes, expressing high-frequency and low amplitude temperatures fluctuations, were visible throughout the study period and across the borehole depth. More

locally, stripes of higher temperature relative to the background temperature coincided well with the testing periods where GGA05 was used as abstraction borehole (Table 3). A stronger warming signal was visible above the submersible pump at c. 25-30 m depth during a longer stepped heat extraction-injection experiment on the 14-15th January 2025.

Above c. 15 m, the DTS time-depth profile recorded high-amplitude temperature variations throughout the study period that were attributed to the effects of seasonal changes in air temperature. These were expressed by warmer temperatures in October ($>13^{\circ}\text{C}$) and cooler temperatures ($<8^{\circ}\text{C}$) from November 2024. DTS timeseries at 0.9 m recorded a maximum temperature at the start of the study period (13.5°C on the 18th September 2024). The near-surface temperature decreased between December 2024 and January 2025 and reached a minimum of 2.4°C on the 10/01/2025, before increasing again to c. 7°C on the 4th March 2025.

In Figure 2a, a good correlation was found between the long-term cooling-warming trends in the DTS timeseries recorded at 0.9 m (black curve) and the daily average air temperatures variations (red curve). Superimposed onto this long-term signal, high-frequency and low-amplitude temperature fluctuations, that may be the expression of the stripes observed in the DTS time-depth profile, were recorded in the near-surface DTS signal. Similar fluctuations, of significantly larger amplitude, were also recorded in the air temperature data. Anomalously high and low temperatures in the DTS data relative to the long-term trend also correlated well with periods of warmer and cooler air temperature. In Figure 2b, DTS data shows that the heat pulse associated to warmer surface temperatures progressively dissipated as it propagated downwards and was overprinted by a ‘cool pulse’ from November 2024.

Figure 3a shows the temperature profiles with depth in GGA05. 14 profiles were selected across and extended period of analysis (January 2024 - March 2025) to better visualise the effects of seasonal changes in temperature. The selected profiles indicated a minimum and maximum surface temperature of 2.5°C and 17.4°C in February and August 2024, respectively. In the October and November 2024 profiles, a maximum temperature of c. 13.5°C was measured between 3 and 5 m, showing the downward propagation of the above-mentioned heat pulse, while the near-surface temperature decreased under the influence of cooling air temperature. At c. 10-15 m, the temperature for all profiles averaged 11.2°C (standard deviation $< 0.08^{\circ}\text{C}$), below which the apparent temperature gradients became linear, with a best fit of c. $13^{\circ}\text{C}/\text{km}$.

Figure 3b shows the average temperature calculated along a depth profile for the study period (Sept 2024 – Mar 2025), compared to the average temperature from the earlier available time periods of DTS acquisition in

GGA05 (Jan - Aug 2024). During this earlier period, GGA05 was used as a mine water abstraction borehole for a series of heat abstraction experiments involving cold water injection in the Glasgow Upper mine working. These average temperature profiles were calculated to smooth out the signals induced by short-term heat injection-abstraction tests during the study period and investigate potential long-term disturbances induced by a 5-day heat injection experiment in the Glasgow Main (injection at GGA08) conducted at the start of September 2024 (Gonzalez Quiros et al., 2025).

Using the average temperature profiles, a general best-fit temperature gradient of $13^{\circ}\text{C}/\text{km}$ was estimated. The profiles can however be divided into five intervals with different best-fit gradients for each interval.

- 1) The topmost interval (down to 15 m) is subject to the influence of seasonal variations in surface temperature. The calculated average temperature therefore highly depends on the considered time interval. As the surface heat pulse signal is attenuated with increasing depth, the discrepancies between both profiles are reduced, reaching an average of 11.2°C at 15 m, in accordance with the value reported in Starcher et al. (2019).
- 2) At 15 m, the borehole encounters the Paisley Clay Member formation and a best-fit linear temperature gradient of $20^{\circ}\text{C}/\text{km}$ was estimated for both average temperature profiles down to the base of the formation at c. 26 m, where the temperature averages 11.4°C .
- 3) Below the base of the Paisley Clay Member, the best-fit temperature gradient of c. $13^{\circ}\text{C}/\text{km}$ corresponds to the estimated best-fit for all profiles during the study period, down to the Glasgow Upper Coal where $T = 11.7^{\circ}\text{C}$.
- 4) Between the Glasgow Upper (51 m) and Ell Index Coal (58 m), which coincides with a sandstone dominated interval, the average temperature was relatively uniform and deviated from the temperature predicted by the $13^{\circ}\text{C}/\text{km}$ gradient by up to 0.6°C for the Jan-Aug 2024 profile and 0.04°C for the Sept 2024-Mar 2025 profile.
- 5) Below the Ell Index Coal, the discrepancies between both profiles progressively increased in a clay- dominant interval, with the apparent best-fit gradient for the Sept 2024-Mar 2025 profile being higher (c. $14.5^{\circ}\text{C}/\text{km}$) than the Jan-Aug 2025 profile (c. $11^{\circ}\text{C}/\text{km}$), down to the top of the slotted screen. There, the Sept 2024-Mar 2025 profile matches the temperature predicted by the $13^{\circ}\text{C}/\text{km}$ gradient (c. 12.15°C), depicting a 0.1°C warming relative to the Jan-Aug 2025 profile.

Below the top slotted screen depth, the FO cable enters in contact with water. Across the screened interval, constant average temperatures of 12.08°C and 12.2°C were calculated for the Sept 2024-Mar 2025 and Jan-Aug 2025 periods, respectively.

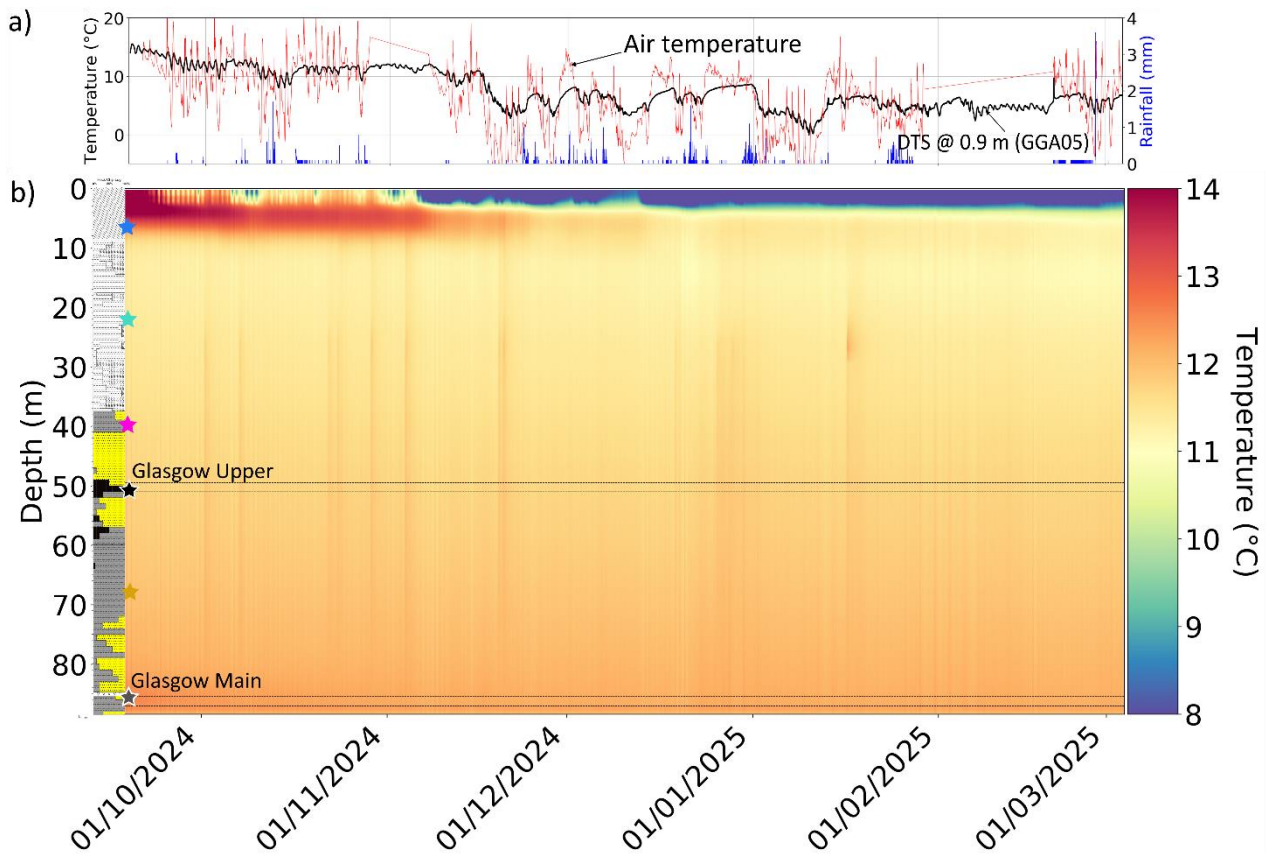


Figure 2: DTS in GGA05 showing a) the temperature change at 0.9 m compared to the air temperature and average rainfall at the weather monitoring station at the UKGEOS Observatory, and b) the temperature variation in GGA05 between the 13th September 2024 and the 4th March 2025. The colored stars indicate the depth of the time series displayed in Figure 5. The dashed lines indicate the depth of the Glasgow Upper Coal and Main mine working.

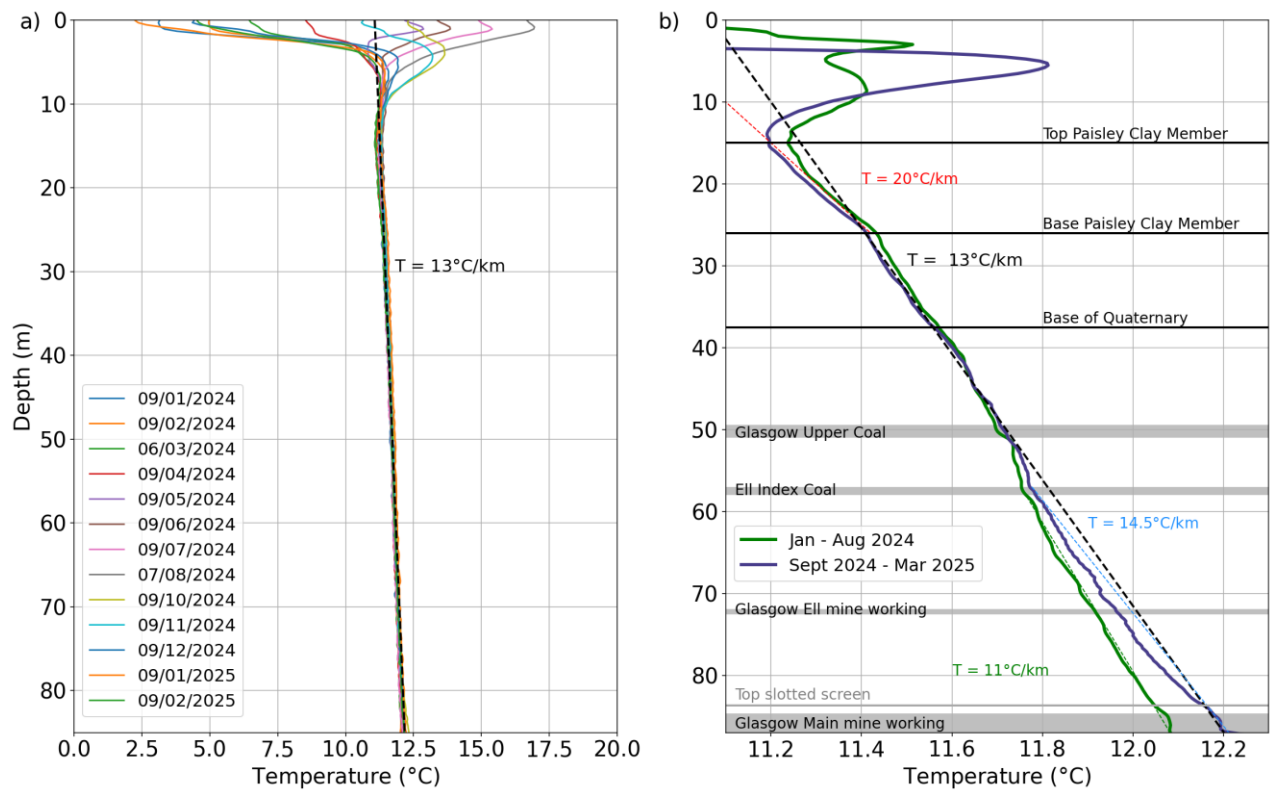


Figure 3: a) Temperature profiles in GGA05 at 14 selected dates between January 2024 and February 2025 and b) temperature profiles showing the average temperature over the January-August 2024 and September 2024-March 2025 periods and the best-fit temperature gradients for different depth intervals, together with the location of the mine workings.

3.2 Temporal Temperature Variations

Figure 4 and 5 shows the temperature changes recorded by DTS during the study period, focusing on the period starting 7th November 2024 at different depths of boreholes GGA05 and GGA08, respectively. Each time series is associated to a specific lithology to evaluate the impact of lithological changes on the magnitude and rate of temperature variations. For GGA05, these are reported as coloured stars in Figure 2b. Whilst the recorded temperature increases with depth for most lithologies, DTS observations at the depth of the made ground (i.e. down to 8 m) tends to follow a different behaviour, described further in each respective section.

3.3.1. Thermal response at GGA05

In the period starting 7th November 2024, borehole GGA05 was used to abstract water from the Glasgow Main in various tests (4 cooling, 1 heating and 1 pumping tests) conducted at the Observatory (Table 3). For all tests, the DTS signal recorded a slight increase in temperature across the whole borehole depth

independently of the nature of the experiment (Figure 4). The amplitude of the temperature increase varied with depth, and it was more pronounced for the shallower, and lower conductivity lithologies (i.e. clay, shallow mudstone, GU). Between the tests, the temperature remained relatively stable for all lithologies following the thermal recovery phase.

At the depth of the made ground (c. 8 m), an average temperature of 12°C were observed until early December 2024, similar the temperature observed in the Glasgow Main at 85 m. The temperature progressively decreased between December 2024 and January 2025, in accordance with the observed variations in air and near-surface temperature, until reaching a minimum of c. 11.2°C that equals the temperature measured at the depth of the clay at 22 m (Figure 4). As shown in Figure 2, the DTS observations in the made ground are located within the interval described as the zone of influence of the seasonal changes in air temperature.

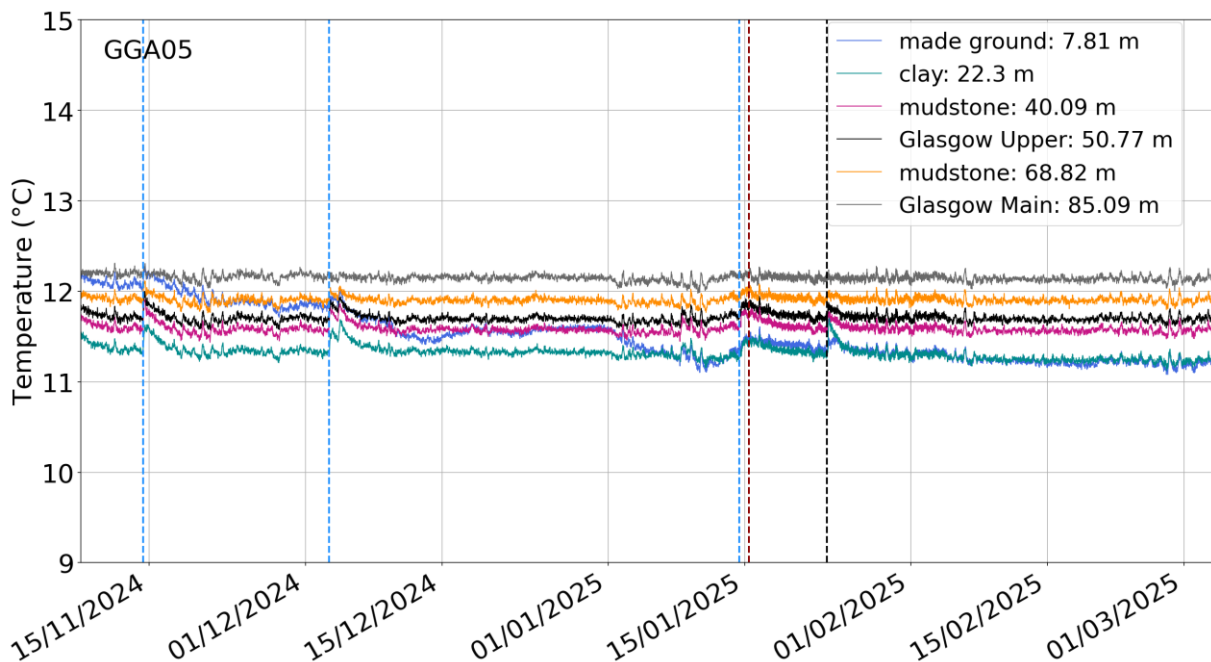


Figure 4. Temperature time series at selected depths in borehole GGA05 (abstraction site 2) during the period of analysis (7th November 2024 - 4th March 2025), showing the temperature change at the depth of the made ground, superficial deposits (clay), shallow mudstone, Glasgow Upper Coal, deep mudstone and Glasgow Main mine working (screened interval). The red, blue and black vertical dashed lines indicate the heating, cooling and pumping tests, respectively.

3.3.2. Thermal responses at GGA08

Borehole GGA08, located c. 110 m away from GGA05, was used as injection borehole for most tests conducted between the 7th Nov 2024 and 4th Mar 2025, including 9 cooling, 4 heating and one pumping tests (Table 3). For all observation depths in GGA08, temperature peaks and lows were recorded in the DTS signal in response to heating and cooling, respectively. Between the experiments, a state of quasi-equilibrium was reached for all observation depths after c. 7 days, with temperatures ranging from c. 11.3°C for the clay to c. 11.9°C for the Glasgow Ell mine working (Figure 5).

Lower average temperatures were reached at the end of the recovery period following a 5-day long cooling test on the 8th January. Following the 13th -16th January tests, slightly higher equilibrium temperatures relative to the pre-test temperatures were reached at the depth of the Glasgow Ell mine working. The thermal recovery rate varied depending on the lithologies. It appears slower for the Glasgow Upper Coal relative to the deep mudstone. The thermal recovery also differed for the made ground, that showed larger cooling under the suggested influence of seasonal temperature variations.

3.3.3. Logger temperature and water level

The water level and downhole temperature were recorded during the period of analysis by a downhole logger installed in GGA08. Those are shown in blue and black in Figure 5, respectively. The logger temperature tends to fit the DTS observations at the depth of the deep mudstone (c. 68 m). In November-December 2024, the downhole logger temperature depicted a quick return to an equilibrium temperature following the heat abstraction/cooling tests, that matched the rate measured by DTS. Larger discrepancies were observed for the recovery period following the 15-16th January heat injection test, where a delayed and slower cooling rate was measured by the temperature logger relative to the DTS observations at 68 m. During the stepped heating/cooling test, a minimum and maximum logger temperature of 6°C and 22°C were recorded in GGA08, for a minimum and

maximum DTS of 9.5°C and 14.6°C at the depth of the mudstone (68.28 m) and of 9.7°C and 14.7°C at the depth of the Glasgow Ell mine working (76.2 m), on the 13th and 16th January 2025, respectively.

Water levels, calculated from the pressure logger installed in GGA08, indicated an average of 10.2 m in the Glasgow Main (blue line in Figure 5). During both heating and cooling tests, DTS peaks and lows were all associated to a rise in the groundwater head in the Glasgow Main mine working, resulting from the injection of water in GGA08. Outside testing periods, DTS also depicted variations that may be correlated to the rise or lowering of the groundwater head or water column in the borehole under natural hydraulic processes. An example of this was particularly visible on the 1st of January 2025, where the rise in groundwater head was observed simultaneously to an increase in DTS at all observation depths.

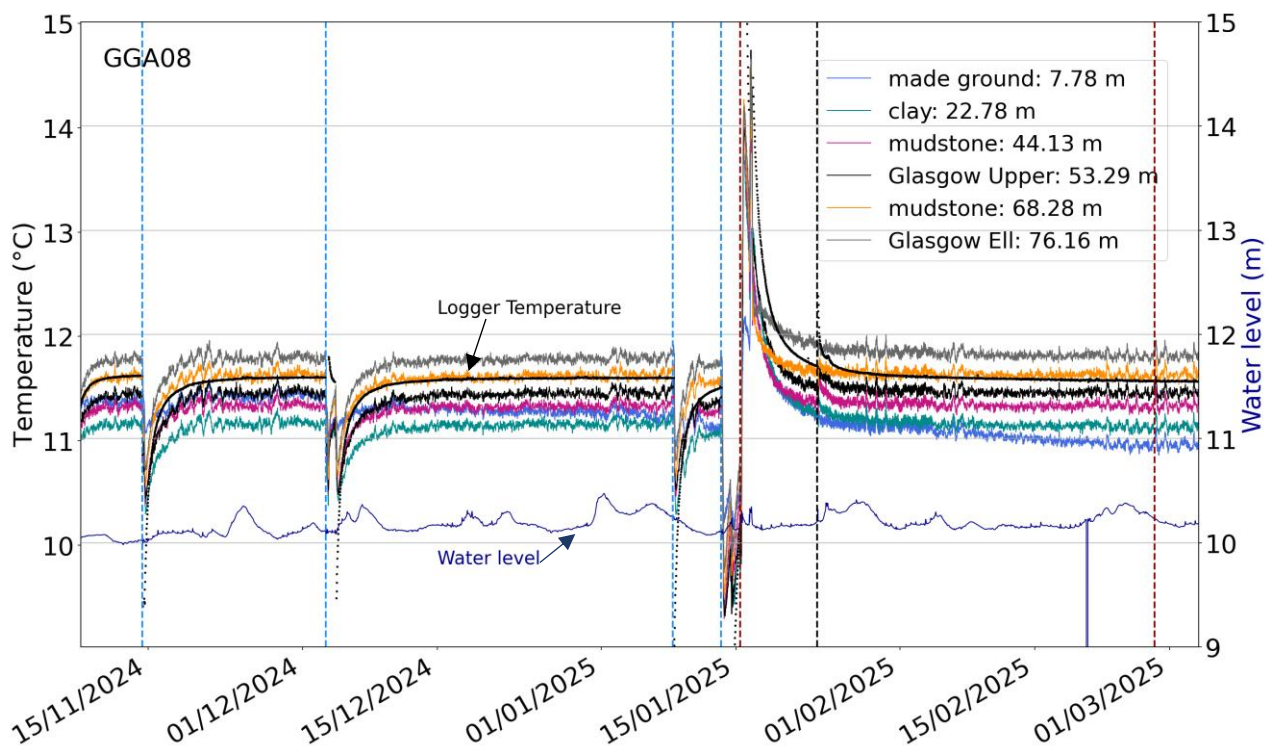


Figure 5. Temperature time series at selected depths in borehole GGA08 (Injection site 3) during the period of analysis (7th November 2024 - 4th March 2025), showing the temperature change at the depth of the made ground, superficial deposits (clay), shallow mudstone, Glasgow Upper Coal, deep mudstone and Glasgow Ell mine working. All temperatures are measured along cased and grouted sections of the borehole. The downhole logger temperature and groundwater head in the Glasgow Main were calculated from pressure logger in GGA08. The red, blue and black vertical dashed lines indicate the heating, cooling and pumping tests, respectively.

4. DISCUSSION

4.1. Controls on subsurface temperature

The temperature profile and temperature change during baseline monitoring is the combination of the natural upward flow of geothermal heat, of the downward heat flow caused by surface temperature changes (down to c. 15 m), as well as the heat transport by fluid flow. The rate at which heat is transported highly depends on both the thermal conductivity of the lithologies encountered

and the system heterogeneity, and the dynamic changes of the system either as natural fluctuations (mainly air temperature) or caused by groundwater flow (especially from geothermal operations).

GGA05 has been used for water abstraction only, and therefore the subsurface thermal disturbances around this borehole are likely to be negligible relative to the ones induced in the heat injection borehole (GGA08) which will be subjected to higher temperature changes relative to the natural state. Nevertheless, the results

indicate that the subsurface temperatures are remarkably stable during the study period and only change by a small amount following short pumping and heat injection/abstraction tests. Breaks in slopes in the estimated average geothermal gradient correlate well with the location of the main lithological boundaries, and more particularly the location of low conductivity layers such as the mined or unmined coal layers and clay intervals (e.g. consistent shifts towards lower temperature observed where the borehole intersects the Glasgow Upper Coal and Ell Index Coal).

The large discrepancies between the Jan-Aug 2024 and Sept 2024-Mar 2025 profiles at 51 m – 83 m, in the low conductivity clay-dominated interval (Figure 3b) suggest long-term thermal disturbances linked to the use of GGA05 as an abstraction borehole during a heat injection experiment at the start of September 2024. Warming of the rock mass overlying the mine workings may occur as a result of the upflow of warmed water injected at GGA08 (GMA) into the abstraction borehole following thermal breakthrough, and the diffusion of heat through the borehole walls. These disturbances appear to be more pronounced in the lower half, clay-dominated section of GGA05, suggesting that groundwater flow in the mines due to geothermal operation can impact the thermal state of the system over large areas and extended time period, especially where the rock thermal conductivity is lower.

Under natural conditions, increases in temperature measured by DTS were associated to the rise of the groundwater column in the borehole, bringing warmer water at shallower depth under the effect of pressure diffusion. These may be linked to a combination of natural processes, such as changes in barometric pressure or tidal strain (Monaghan and Spence, 2023).

Yearly fluctuations in air temperature have a direct effect on the temperature down to 15 m, i.e. down to the depth of the Paisley Clay member, that may represent a lithological boundary to further downward diffusion of the surface temperature signal. At c. 15 m, the long-term temperature calculated for GGA05 averages 11.2°C, which is 1°C higher than the annual mean air temperature of 10.2°C calculated using data from the Paisley weather station over the March 2024-March 2025 period. Pleistocene climate warming following glacial suppression of temperatures has also been identified as the cause of a lower apparent geothermal gradient above 200 m. In the Glasgow area, studies have shown that uncorrected geothermal heat flux may be underestimated by c. 20 mW/m² due to paleoclimate effect (Westaway and Younger 2013; Busby and Terrington 2017, Watson et al., 2020). Anomalous temperatures at depth were also suggested by Watson et al. (2019) to result from Urban Heat Island (UHI) effect, described as the record of downward heat flow resulting from urban and industrial activity, that took place during the 19-20th Century at the location of borehole GGC01, located 1.5 km to the NW of GGA05 in an unmined part of the succession (Westaway and Younger, 2016).

4.2. Relevance for geothermal and storage

When no direct measurements from boreholes or shafts are available, determining the thermal state of mines relies on estimates based on the undisturbed geothermal gradient. In UK mining areas, those often rely on a limited number of in-situ measurements of dry rock temperatures, taken when mines were active, or of mine water temperature measured at the depth of the mine workings after flooding of the mine (Farr et al., 2021). Most of these measurements have been compiled in the UK Geothermal Catalogue (Rollin et al., 1987; Fellgett and Monaghan, 2024). However, within the depth range of mine workings, the temperature is susceptible to being disturbed by a number of factors linked to the mining and post mining history, making it difficult to determine a reliable estimate of the geothermal gradient (Watson and Westaway, 2020). These include potential cooling of the rock mass due to air ventilation implemented during the mine activity, or disturbances of the heat flow due to groundwater flow in interconnected open voids during, and after, water rebound (Monaghan et al., 2026).

Monitoring the long-term temperature changes via DTS gives the opportunity to characterise the thermal response from different lithologies, at different depths, to heat injection or abstraction. These experiments can be interpreted in a similar way to Thermal Response Tests to refine the thermal properties of different lithologies and understand their heat storage capacity. This has been conducted before for sandstone aquifers (e.g. Herrera et al., 2018) but has not, to our knowledge, been applied to mine water systems outside the Glasgow Observatory. Changes in the downhole logger temperature can be used to link the DTS response at various depths to the variation in mine-water temperature and interpret the rate of diffusive heat transfers between the borehole and surrounding rock to refine the subsurface properties. In GGA08, slower return to equilibrium observed for low conductivity lithologies such as coal (e.g. at the Glasgow Upper Coal) and clay intervals after a cooling or heating test highlights the higher storage potential of these lithologies relative to sandstone dominated intervals. The time lag observed between changes in the logger temperature and the DTS response (Figure 5) may provide insights into the effect of the borehole construction or different hydraulic processes, such as a slower return to equilibrium via free heat convection in the borehole versus heat recovery via heat conduction through the borehole walls and rock mass.

5. CONCLUSION

This study has presented results from fibre optic distributed temperature sensing (DTS) monitoring at the UK Geoenergy Observatory in Glasgow. DTS data from two of the mine water boreholes during a period of six months has been used to characterise the thermal state of the mines and overlying bedrock and superficial deposits and the changes caused by effects of both natural processes and geothermal experimentation. A temperature gradient of c. 13°C/km down to the depth

of the deeper mine workings at 84 m has been estimated. The dataset has also shown the effect of seasonal influence of temperature variations down to c. 15 m and the influence of lithological changes on the general geothermal profile. The variation of heating / cooling rates with depth during and after geothermal tests showed that DTS can provide valuable insights about the subsurface distribution of properties and the link between hydraulic and thermal processes at various scales. Further investigation on the relative contribution of the geothermal and surface heat flux, groundwater flow and relationship between temperature and pressure changes on the thermal state of the mine, combined with estimation of thermal properties using the distributed temperature data can be used to better understand the heat transfer mechanisms in mine water systems and characterise the sustainability of heat abstraction and/or storage.

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