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First results from a ground source heat pump monitoring project at the British Geological Survey Headquarters in Nottingham, United Kingdom

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ABSTRACT

The heating systems of two buildings at the British Geological Survey's campus in Nottinghamshire, UK, have been retrofitted using ground source heat pump technology. Low grade heat is extracted from the ground using 28 vertical closed-loop borehole heat exchangers installed to c.225 m. Two buildings are served by separate ground arrays with one coupled to two 60 kW heat pumps and the other to three 60 kW heat pumps, providing up to 300 kW peak heating capacity.

Six of the boreholes are monitored using fibre optical distributed temperature sensing (FO-DTS) cables. The cable is also capable of distributed acoustic sensing (DAS) and active heating for formation characterisation including Enhanced Thermal Response Testing (E-TRT). Five of the wells have electrical resistivity tomography (ERT) capability using BGS's PRIME monitoring system designed in-house. This enables time-lapse cross-hole tomography for 4D inversions to characterise geological heterogeneity, track natural seasonal processes and induced thermal changes in heat exchanger wells across a rock volume of approximately 360,000 m^3. The thermal energy extracted from the ground and produced from the heat pump is measured with heat flow meters. Electrical consumption of heat pumps and circulation pumps is monitored enabling calculation of COP's and Seasonal Performance Factors, to enable breakdown of OPEX costs for each system. One borehole within the array was cored to 238.5 m and the hole was logged with a comprehensive suite of geophysical tools to confirm the geological sequence and vertical variations in geophysical properties.

We found that modelled and observed results of the thermal conductivity of the bedrock also differed depending on how the assessment was made. Specifically, TRT gave an effective ground thermal conductivity of 2.33 W/mK vs laboratory analysis of core material which gave variable but generally higher values. The presence of gypsum in Mercia Mudstone formations probably reduces bulk thermal conductivity. The impacts of groundwater flow, concurrent well installation during monitoring and subtle variations in bedrock competence are also discussed. This data feeds into the site thermogeological model and supports numerical models and public outreach resources.

1. INTRODUCTION

The UK Natural Environment Research Council (NERC-UKRI) has a target to decarbonise its heating systems by 2030 and achieve Net Zero carbon emissions by 2040. The space heating of two office buildings on the British Geological Survey's Keyworth Campus in Nottingham, UK, has been decarbonised using ground source heat pump (GSHP) technology.

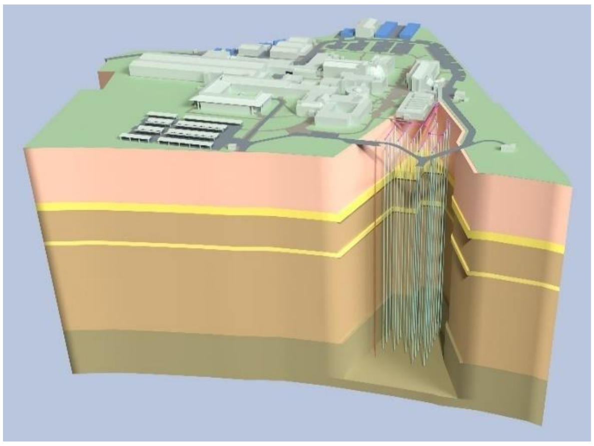

Figure 1: Model of the BGS Keyworth Campus site depicting layers within the Mercia Mudstone Group and GSHP boreholes. BGS © UKRI.

Heat is extracted using 28 vertical closed-loop borehole heat exchangers installed to 225 m with 6.3 km of loop in total, plus ~2 km of shallow trench pipes. The ground arrays are coupled to five 60 kW heat pumps, providing up to 300 kW total peak heating capacity for office building, meeting rooms and a canteen. All boreholes are backfilled with cement-based bentonite geothermal grout to provide good thermal coupling with the ground, to seal the holes to minimise unwanted interactions with bedrock and protect the deep Sherwood Sandstone Group aquifer.

The site comprises over 200 m Triassic mudstones (Mercia Mudstone) overlying a principal aquifer (Sherwood Sandstone) (Figure 1). The Mercia Mudstone comprises red silty mudstone with frequent gypsum nodules and mineral veins, with occasional thin grey-green siltstone and sandstone beds (skerries). Variations in sedimentology result in a characteristic down-hole geophysical log signature and allow the MMG to be split into seven distinct stratigraphical units. The lower part of the MMG is characterised by interbedded siltstone and fine sandstone between 180-215 m (Tarporley Siltstone Formation, a secondary aquifer). The MMG overlies the Triassic Sherwood Sandstone principal aquifer between 215-231 m, which comprises weak to moderately weak yellow medium-grained pebbly sandstone.

The GSHP project started in early 2023 with building heat loss calculations, ground surveys and planning permissions. A desktop study of available geological and thermogeological information guided design and planning. The feasibility studies considered the merits of open loop and closed loop systems and although the Sherwood Sandstone aquifer was suspected to be present at ~215 m depth, and a minor aquifer at the base of the Mercia Mudstone (Tarporley Siltstone) from ~185 m, the anticipated flows were not considered likely to meet the estimated peak heat loads, and so a vertical closed loop borehole heat exchanger (BHE) system was selected as the preferred geothermal technology. In summer 2023 a 240 m deep TRT test borehole was drilled and a 231 m single 45 mm diameter U-loop was installed. The borehole was backfilled with ConnectPlus bentonite-sand blend grout in the upper 180 m and 10 mm dia. gravel backfill between 180-240 m (across the lower zone of drill flush loss and suspected sandstone layers). A month later an TRT was performed to assess drillability and ground conditions, to confirm the geology/soil profile, and measure ground thermal properties to assist the detailed GSHP design.

The drilling works encountered difficult ground with unstable zones between 60-90 m depth in the Mercia Mudstone (due to a weak zone of destructured and fractured gypsiferous mudstone), and various mechanical issues were encountered: out of 32 wells, 4 were abandoned, a 12.5% failure rate. Failure was associated with stuck and snapped drill casing, use of polymer-based drilling fluid rather than a well-controlled bentonite mud system, and one unclamped loop dropping overnight before grouting and failing its pressure test. The GSHP system commissioning was undertaken through April 2025.

This paper introduces the project for the first time and describes geological and thermogeological characterization methods and first results from the GSHP facility. It is planned to continue monitoring the GSHP system over its operational lifetime and feedback outcomes to the geothermal community.

2. Methods

Thermogeological Characterization

In addition to the TRT, the shallow geothermal resource was further characterised by using a range of geophysical methods and by extracting and analysing core samples. One of the production wells (BH3, officially called ‘Keyworth D’) was continuously cored by WellTherm Drilling Ltd at 4" diameter (102 mm ID) between 2-238.5 m using the Geobore-S wireline coring method and water flush to minimise chemical and microbial contamination of the core. The 1.5 m long cores were stored in a 5°C fridge within ~4 hrs of extraction to slow microbial growth. The cores were cut within 24 hrs of extraction with a saw using minimal amounts of deionised water into 1 m and 0.5 m lengths and end caps sealed and taped for safer handling and then transferred into 1 m boxes and accessioned in the National Geological Repository at BGS Keyworth. Using aseptic techniques, quarter cores ~10 cm long were taken approximately every 6 m down the core. One quarter was sealed to retain moisture, transferred to a 19°C lab and left for >24 hrs to thermally equilibrate before testing for thermal properties using a CTHERM (Canada) Trident analyzer using the Modified Transient Plane Source Method (MTPS) sensor. All samples were also tested for bulk density using the submersion method following ISO British Standards methodologies.

Six of the wells had wireline downhole geophysical surveys performed by European Geophysical Services (EGS) to characterise formation geophysical properties and correlate geology to evaluate any structural features such as dip, fractures, and faults. In June 2024 the fresh solid cores from Keyworth D core underwent non-destructive testing in BGS’s onsite core scanning facility (www.ukgeos.ac.uk/core-scanning) with radiographs taken at 0°, 45°, 90° angles to reveal the internal structure, density and textual variations, and map fracture state while the rock material was in relatively fresh condition. Next the core lengths were scanned through the PVC liner using a Multi-Sensor Core Logger Standard system (MSCL-S) to measure geophysical properties including gamma density, magnetic susceptibility, and natural gamma activity every 2 cm. The cores were immediately returned to the fridge after scanning at room temperature to limit moisture loss and micro-mechanical damage. The stratigraphy was interpreted by comparing the gamma logs with field logs collected in nearby BGS reference boreholes (i.e. Cropwell Bridge; Bloodworth and Prior 1993). The location of all wells, including the abandoned wells, were surveyed to 2 cm accuracy using a Leica GNSS dGPS unit. Grout sub-samples (Muoviterm) were taken during grouting stages for additional material property testing (thermal conductivity, bulk density, electrical resistivity) for QC purposes and to inform parameters for future borehole heat exchanger and Enhanced TRT modelling studies.

Temperature Monitoring

The TRT well (BH1) had three repeat temperature profiles taken by lowering a Solinst 107 TLC meter down into the water-filled loop pipe slowly meter by meter. The first was in September 2023 one month after the end of the TRT test, the second was in January 2024, and the third was in May 2024. The TLC meter has a measurement accuracy of around 0.1°C.

The undisturbed baseline ground temperature profiles in the five monitored production wells were measured using multimode fiberoptic cables within a hybrid cable, cable-tied on to the outside of the return from ground side of the loop pipes every 0.5 m, as shown in Figure 2.

Figure 2: Photo of the 40 mm OD loop pipes and typical arrangement of sensor cables. The stainless-steel tubes with red end caps are ERT electrodes fixed to the 'inflow to ground' loop pipe, the black cable behind is the hybrid fibre optical cable tied onto the 'return from ground/production' side of the loop pipe. The blue 32mm pipe is a ~100 m long shallow tremie and the black 32mm pipe behind it is the ~210 m long deep tremie. The blue clip is an "Ez-Snap" placed every 1 m to keep the loop pipes separated. BGS © UKRI.

Baseline measurements were performed with a Silixa Ultima-M DTS unit set up in a temperature-controlled room. The first pre-baseline surveys were 29-31 October 2024 once the wells had been backfilled with geothermal grout but while production boreholes were still being drilled 10-40 m away. The final baseline was 12 March 2025 once loops were installed and grouted. The FO-DTS measurements were all run in double ended configuration with 60 s averaging (30 s x 30 s) repeated over 1 hr to check stability. This configuration returns integrated temperature values every 0.254 m along the cable with ~0.01°C accuracy.

Electrical Resistance Tomography

Five loop pipes were each fitted with a single Electrical Resistivity Tomography (ERT) cable with a 2.5 m vertical electrode spacing with the first electrode located at ~220 m below ground surface, to enable time-lapse monitoring of ground electrical resistance properties between boreholes spaced ~25 m apart. Measurements were made using a BGS-designed PRIME monitoring system (Chambers et al., 2022). This novel method enables volumetric monitoring of seasonally driven changes in ground moisture content as well as temperature changes driven by heat extraction. The wells are spaced approximately 25 m apart in a north-south-east-west pattern. The installation of the sensor cables and removal of all temporary steel drill casing required close coordination and collaboration between the drilling contractor, fibre optical installer, and client. Omega-shaped EZ-Snaps (Geo-air industries inc. Canada) spacers were installed every 1 m along the 40 mm dia. geothermal probes, as shown in Figure 2, for three main reasons; (1) to keep the flow and return pipes apart to reduce thermal short circuiting and ensure close contact with the geological formation, (2) to act as a shield to protect the delicate sensor cables from abrasion and snagging during installation – particularly in the unstable unit between 60-90 m, (3) to provide a fixing point to attach the deep tremie pipe to keep it straight to reduce the chances of snagging on any sharp rock ledges during installation, (4) this arrangement also stiffened the whole loop assembly, allowing it to push through any obstructions. The bottom of each monitored loop was weighed down by attaching electrically insulated steel rebar lengths and 15 kg bottom weights (to not affect the ERT system) and the pipes filled with water to overcome buoyancy.

The 231 m TRT well (BH1) is located 5 m away from the production well (BH2) outside the main array and was repurposed as a monitoring well with a FO-DTS cable installed down one of the 45 mm OD loop pipes in May 2025. This well acts as a control point and over time may sense thermal interference from the main bore field wells and providing data to validate numerical models. The instrumented wells can also be accessed for research purposes (E-TRT).

Heat Pump Monitoring

The thermal energy extracted from the bore field is calculated using ultrasonic heat flow meters (3.5% accuracy) with PT100 pocket sensors (+/- 0.1C accuracy) inserted into the plantroom pipework. Heat flows are also monitored at the heat pump outlet to the 1500 L thermal stores and between the thermal stores and the building. Electrical consumption of all heat pumps and circulation pumps is automatically monitored enabling calculation of real-time heat pump Coefficient of Performance, and Seasonal Performance Factors (SPF1-2).

3. RESULTS

Geology

The geology proven in Keyworth D borehole was 215 m of Triassic Mercia Mudstone Group (MMG) resting on 25 m of Triassic Sherwood Group sandstone. The formation depths and thicknesses are summarised in Table 1. Lithostratigraphic boundaries were picked mainly based on interpretation of downhole geophysical logs (Natural Gamma, Density & Resistivity), MSCL-S core scanning data (Gamma, Density, Magnetic Susceptibility), and initial logging through clear plastic liners. The core had not been slabbed and logged in detail at time of writing because it is being temporarily preserved in a fridge to minimise mechanical damage or drying out while awaiting further geomechanical, pore fluid, and other advanced scientific analysis.

Hydrogeology

The static water table in the confined Sherwood Sandstone Group aquifer was around 40m below ground level (~25 m asl) in most of the boreholes. Reconnaissance water sampling in the sandstone section of Keyworth D at 215 m found the water to be brackish. Shallow groundwater flows were also observed between 10-20 m flowing along a mudstone-gypsum karst interface.

Ground Temperature Monitoring

Seasonal monitoring of the TRT well temperature profile and repeat baseline monitoring of the five GSHP production wells using the FO-DTS system provided accurate undisturbed ground temperature profiles prior to any heat extraction. The undisturbed temperature profile of BH5 is shown in Figure 3, which illustrates the inverse temperature gradient with bottom hole temperatures of around 13.5°C at ~220 m depth. Interestingly, the FO-DTS baseline profiles from October 2024 and February 2025 differ noticeably in the 10-100 m depth zone with ~0.4°C cooling witnessed in the period three months after grouting and nine months after grouting.

Table 1: Summary of strata encountered in Keyworth D borehole (SK63SW150) based on Gamma logs. Following stratigraphic naming system of Howard et al. (2008).

Group	Formation name	Depth m	Thickness m
Mercia Mudstone Group	Branscombe Mudstone Formation; silty mudstone with up to 50% nodular gypsum and veins	0-50 m	c.50 m
	Arden Sandstone Formation: thin fine-grained sandstones	50-55 m	c.5 m
	Sidmouth Mudstone Formation (upper): silty mudstone with gypsum veins	55-91 m	c.38 m
	Cotgrave Sandstone Member: sandstone	91-95 m	c.4 m
	Sidmouth Mudstone Formation (lower): silty mudstone with some gypsum veins	95-165 m	c.91 m
	Radcliffe Member	165-180 m	c.15 m
	Tarporley Siltstone Formation; laminated mudstone, siltstone, thin sandstones	180-215 m	c.35 m
Sherwood Sandstone Group	Nottingham Castle Formation: pebbly sandstone	215-238.5+ m	>25 m

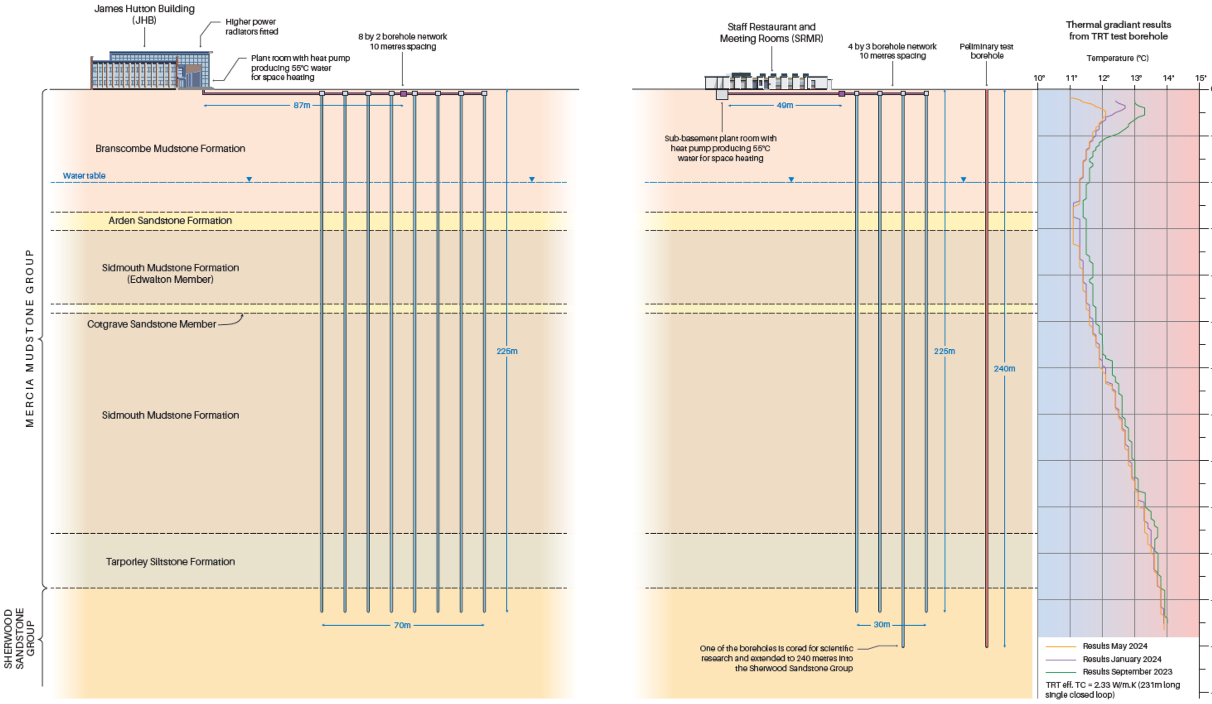

Figure 3: Schematic cross section through the ground at the Keyworth Campus GSHP scheme showing baseline temperature profile measured in the TRT well. BGS © UKRI.

TRT results

The in-situ thermal response test (TRT) was performed by Qvantum Solution Design Ltd via Kensa Contracting Ltd and the 70 hr heating test returned a bulk thermal conductivity of 2.33 W/mK. The geology of the TRT well (inferred from Keyworth D and 0-103 m of geophysical logging) is the same as the main GSHP boreholes; The average thermal power input during the test was 7.8 kW, supplying 38 W/m on average to the ground, with an average flow rate of 0.4 L/sec for 70 hrs with a 4-day cool down period with fluid circulation.

Thermal conductivity testing results

The results of thermal conductivity measurements on core plugs are shown in Figure 4. There is considerable scatter partly due to natural variations in lithology and also orientation of the core plugs relative to the bedding. The Sidmouth Mudstone Formation between 90 m and ~180 m has a higher bulk conductivity than the overlying Branscome Mudstone Formation which is richer in gypsum.

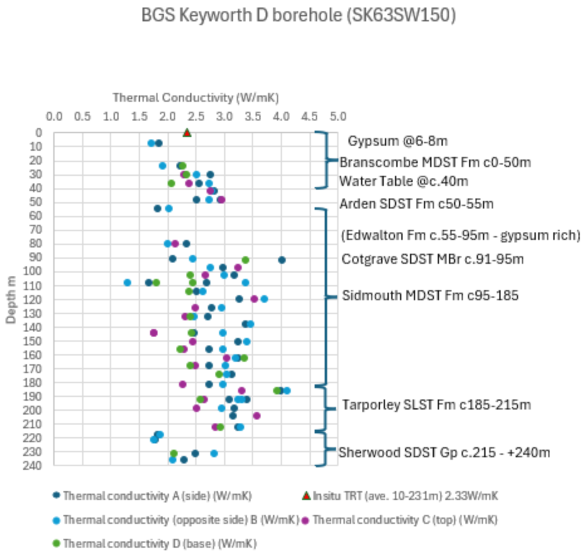

Figure 4: Plot of lab thermal conductivity values measured at different orientations (vertical and horizontal) on Keyworth D core plugs. BGS © UKRI.

Early borehole monitoring results

The early days and weeks of ground source heat pump system operation were captured by the in-well DTS monitoring system which was set to record every 3 min. Figure 5 shows four days of DTS data recorded during the first circulation of the loops (BH2) on the SRMR building array during system commissioning and testing in mid-April 2025. The first 450 min capture a nearly uniform temperature profile because the circulation in the loop is mixing up and homogenising the loop fluid temperature. After 450 min the loop circulation cycle stopped and the well temperatures started to recover, notably cooling in the upper part of the well, with the fastest recovery rates at depths of ~50 m and ~70 m, which are coincident with sandstone beds. The warming in the lower part of the well is because of the ‘C’-shaped thermal gradient and is mainly restricted to the lower aquifer units (Tarporley Siltstone and Sherwood Sandstone).

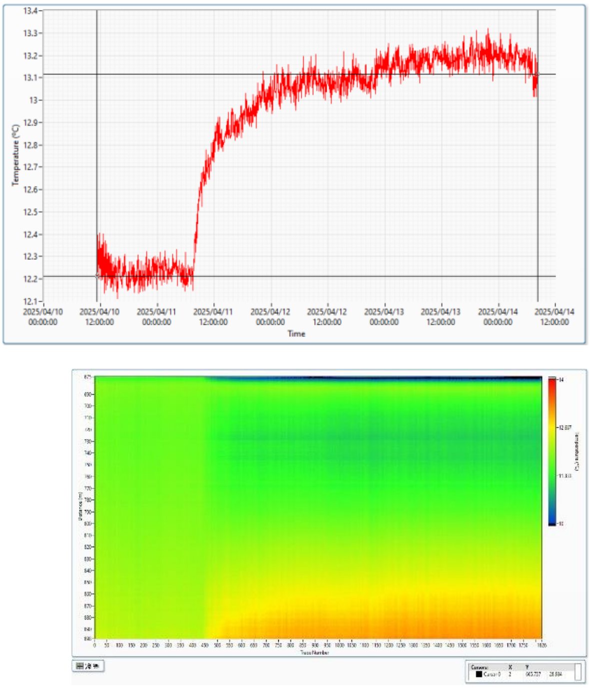

Figure 5: DTS temperature versus time plot at 220 m depth in BH2 showing natural recovery after loop circulation (top). Heat map (scale is 10–14°C) showing FO-DTS temperature along cable installed on outside of loop in BH2 between 10-14 April 2025, during heat pump commissioning (bottom). The period captures homogenisation of the well temp profile on 10th April when glycol was being flowed around the loops to flush the system and test the circulation pumps and the subsequent thermal recovery response on the when flow was stopped the next day on the 11th April. BGS © UKRI.

3. DISCUSSION

The data collected during drilling, commissioning and early heat pump operation is feeding into the improved site thermogeological model, supporting development of numerical models and digital twins, and is enhancing interpretation of the monitoring data. The work contributes to a growing UK portfolio of geothermal projects and tools being developed by BGS and partners (Monaghan et al. 2025).

It is suspected that ongoing drilling activities on the bore field during this period caused some cross flow of drilling fluids between wells along higher permeability horizons (sandstone beds, karst and potentially fractures) and the DTS data has captured this. The most affected zone was restricted to the top 110 m, which is coincident with the upper part of the Sidmouth Mudstone Formation and where the 8″ dia. steel casing was temporarily installed while drilling the well to maintain stability in the collapse prone zone between 60-90 m. There are also discrete zones of localized warming observed in the DTS data between 10 m and 20 m depth in some wells. This depth zone coincides with the depth of conductor casing installed to control flush losses often encountered in the upper ~25 m. Downhole CCTV footage taken during casing extraction shows vertical groundwater flows coming into the well at the dept zone, providing evidence of shallow ground water flow and it is suspected these preferential flows are associated with enhanced secondary permeability pathways that form along the interface between partially dissolved gypsum lenses (micro-karst) and weathered and de-structured red mudstone.

The implication of groundwater flow is two-fold: it may be considered a positive because incoming groundwater will enhance the thermal regeneration of the zone of thermal disturbance around the wells upgradient from the adjacent array. The array downgradient may experience cooling effects of the adjacent array. However, shallow focused groundwater flow can carry a risk of longer-term gypsum dissolution and formation of cavities. In one instance the backfill grout was observed in an un-grouted well, suggesting it had migrated from a well drilled ~2 m away into another. This is evidence of the drilling and grouting process sealing up natural fractures in the mudstone, which will prevent upward and lateral movement of groundwater in the boreholes. The repeat DTS and ERT monitoring will aim to capture any long-term changes to provide a better understanding of these subsurface processes and medium- and long-term geotechnical risks for GSHP installations in this gypsum-bearing geology.

It is predicted that any thermal interference between wells and between the two arrays will be greatest felt along the more conductive sandstone layers (Arden Sandstone and Cotgrave Sandstones) at around 50-55 m, 70 m and 90 m (seen in the DTS plot in Figure 5 as blue horizontal lines) and gypsum karstic surfaces in the upper 25 m. Continued distributed temperature monitoring through winter 2025/26 and into the summer will no-doubt reveal further insights and understanding of system performance and processes of thermal regeneration of the boreholes and surrounding ground between heating seasons.

The undisturbed ground temperature at 200 m measured in the TRT well (Figure 3) and seen in the well DTS surveys was ~13.5°C, which is 2°C cooler than was anticipated by the available regional models (Busby et al. 2011). The wells all have a reverse thermal gradient in the upper 50 m, a phenomenon which has also been observed in Gateshead in the UK (Banks et al. 2009) related to urban heat island effects but may be related to glacial climatic history. This suggests variations from regional models that are developed from legacy third-party data are possible and stresses the importance of taking modern equilibrium measurements to improve predictive models and reduce uncertainty in ground parameters.

The initial warming of the ground shown in the thermal profile in Figure 3 is probably related to heated drilling fluid as it passes through the drill rig pump. It took up to 3 months for the ground to equilibrate thermals after drilling and grouting the TRT well.

The measured field thermal conductivity of 2.33 W/mK was lower than the average value derived from core plugs (Figure 3). We suggest that the relatively high proportion of disseminated, nodular and veined gypsum in the Mercia Mudstone Group occurring locally on the East Midlands Shelf reduces the bulk thermal conductivity because gypsum ($CaSO_4$) has a lower thermal conductivity of around 1.6 W/mK compared to the dominant iron-rich red silty mudstone. This variable in thermogeological properties, controlled by variations in mineralogy and secondary mineralisation history will potentially affect the performance and sizing of thermal collectors, and influence regional heat flow, and so this is a topic worthy of follow-on research. It is suspected that the top 5 to 10 m of the Sherwood Sandstone at the site is weathered and this makes it mechanically weaker than at depth, as it was disintegrating during drilling with pressurised water, resulting in poor recovery. The higher porosity and decalcification of cement may explain the lower thermal conductivity of the sandstone (~2.4 W/mK) compared determinations (~3.4 W/mK) made in the Cheshire Basin at the UKGEOS site in NW England (Boon et al. 2025). This data illustrates the value of high-resolution distributed temperature sensing because it reveals variability in ground behaviour which is not captured by a conventional TRT test.

4. CONCLUSIONS

This paper describes for the first time the geology and thermogeology encountered during the installation of two adjacent commercial-scale (300 kW output) GSHP systems retrofitted into mixed-age public sector campus buildings at the British Geological Survey in Nottinghamshire, UK. The site aims to be an exemplary of adjacent ground source heat pump systems with comprehensive monitoring data to support research and industry best practice. The scientific data collected so far during the test phase, cored research borehole, and early heat pump commissioning phase provides new insights into the geology and thermo-geology of the Triassic Mercia Mudstone Group in the East Midlands Shelf, and has wider relevance as these formations occur onshore across much of England and Northern Ireland as well as offshore in UK waters. 20% of the total length of the boreholes in the ground array are monitored using fibre-optical cables and electrical resistivity tomography. This collocated deployment of technologies is providing exciting new insights into the subsurface geology, hydrogeology, and thermal transport process and enables the thermal impact and recovery rates of larger closed-loop GSHP arrays to be continuously tracked and design assumptions to be validated. The findings of the drilling program, novel core characterisation workflows and test methods, have wider relevance and applications to other Geoenergy technology applications in the Mercia Mudstone and Sherwood Sandstone, including crustal heat flow studies, underground thermal energy storage, CCUS, hydrogen and compressed air energy storage, and deep geological disposal (GDF).

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