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Multi-level geothermal analysis of urban heat-in-place: a Leeds case study

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Abstract

As cities across the UK seek to decarbonise heat and achieve net-zero targets, shallow geothermal energy presents an underutilised yet promising resource. In this study, we evaluate the geothermal potential of the upper 1,000 m of the subsurface beneath Leeds, a major urban centre underlain by Carboniferous sandstone aquifers and abandoned coal mine workings. Using geological maps and legacy borehole data, we construct a 3D subsurface model to carry out a stochastic calculation of the volumetric Heat-in-Place (HIP). Four geothermal targets were assessed: the Elland Flags, Upper and Lower Millstone Grit formations, and flooded mine workings. Our results reveal a substantial median geothermal resource exceeding 1,833,333 GWh of thermal energy, with a total recoverable heat output of over 700 MW (>500,000 home equivalent). The Lower Millstone Grit was identified as the most significant reservoir due to its depth and elevated temperatures, while the shallower Elland Flags and mine water systems offer localised low-temperature potential suitable for near-surface heating schemes. Spatial mapping of HIP indicates favourable alignment between zones of high energy potential and areas of heat demand, supporting the integration of geothermal resources into future heat networks. Our work also highlights key geoscientific and regulatory barriers to deployment and outlines the data needed to reduce uncertainty and enable investment. Overall, this work demonstrates the strategic role of urban geothermal energy in supporting Leeds' transition to a low-carbon heat system and offers a transferable methodology for application in other cities in the UK and beyond.

1. Introduction

The transition to renewable energy and the implementation of sustainable energy systems are essential for addressing climate change and achieving net-zero carbon emissions. Heating contributes significantly to global greenhouse gas emissions (e.g., Berretta et al., 2021) and presents a notable challenge for decarbonization efforts. In the UK, heating for residential and commercial purposes is responsible for approximately 23% of total emissions (Department for Business, Energy & Industrial Strategy, 2021), primarily due to dependence on fossil fuels. To meet the country's 2050 net-zero target, it is imperative to develop and adopt alternative low-carbon heating technologies. Geothermal energy, a largely untapped resource, emerges as a promising candidate in this context (Downing and Gray, 1986; e.g., Bayer et al., 2019; Stober and Bucher, 2021; IEA, 2024).

Geothermal energy provides a reliable and sustainable heating solution by utilizing the Earth's natural heat (Stober and Bucher, 2021). These systems can operate continuously throughout the year, offering heating and cooling for space and water heating with minimal carbon emissions. While deep geothermal sources have been explored in select areas (Jones et al., 2023; e.g., Gutteridge Peter et al., 2024; Turan et al., 2024), the potential of shallow to mid-depth geothermal systems, located within the top ca. 1,000 meters of the Earth's subsurface, remains insufficiently investigated, especially in urban environments. These systems are particularly advantageous in cities where energy demand is high, and infrastructure needs are complex (e.g., Akhmetzyanov et al., 2021; Verhaegen et al., 2023).

The shallow subsurface is being increasingly utilized for geothermal energy production globally, particularly through application of ground-source heat pumps. Shallow geothermal energy may be accessed by closed-loop borehole heat exchangers everywhere (Figure 1, left). However, higher flow rates from open-loop wells in aquifers and mines (Figure 1, centre and right), and the option for Aquifer Thermal Energy Storage (ATES) systems (e.g., Fleuchaus et al., 2018), are attractive for larger scale energy provision. ATES systems in the Netherlands and geothermal projects in Germany and Canada demonstrate the potential for leveraging the subsurface for renewable energy (Willems et al., 2017; Fleuchaus et al., 2018; Mitali et al., 2022). Although ATES has potential to support the decarbonisation of heating and cooling in the UK, its deployment remains minimal. Currently, only eleven low-temperature ATES systems are in operation nationwide, collectively supplying just 0.01% of the country's heating demand and 0.5% of its cooling needs (Jackson et al., 2024). Abandoned coal mines in the UK on the other hand have been utilised and repurposed for geothermal heat recovery, such as in Glasgow and Gateshead (Banks et al., 2022; Monaghan et al., 2022), using mine waters as low-carbon heat sources.

However, high capital costs and both real and perceived risks associated with project development have historically acted as barriers to geothermal deployment (Government Office for Science, 2024; ARUP, 2025). In addition, increased subsurface use introduces challenges regarding competing demands on finite resources. Thermal interference between multiple users or overlapping systems can reduce efficiency and lead to resource conflicts, particularly in dense urban areas (Bloemendal et al., 2014; Patton et al., 2020). Hydrogeochemical issues, including scaling, precipitation, and alterations, pose risks to infrastructure integrity and water quality (Farr and Busby, 2021; Banks et al., 2022). Environmental concerns such as subsidence and contamination can result from poorly managed systems, potentially damaging ecosystems and infrastructure (Patton et al., 2020). Additionally, regulatory and ownership ambiguities surrounding subsurface heat further complicate increased deployment, creating legal challenges that must be addressed, particularly in densely populated urban environments (e.g., Akhmetzyanov et al., 2021). Mitigating these risks through planning, monitoring, and governance frameworks requires robust understanding of the subsurface geology for sustainable and efficient use of the shallow subsurface.

In this context, Leeds offers a convenient case study and compelling opportunity to examine geothermal potential and challenges in urban setting. Its shallow subsurface (i.e. upper 1000 m) comprises several aquifers and abandoned mine workings at different depths, offering diverse options for both heat extraction and storage (Figure 1). Located in Yorkshire, Northern England, Leeds has a high population density and diverse subsurface geology, including the Coal Measures and the Millstone Grit formations (Cooper and Gibson, 2003). Positioned within the Pennine Basin, the area offers the potential to study the geothermal potential of various aquifers (e.g., Elland Flags, Rough Rock) and mine water (i.e., flooded old coal mines). Leeds is also actively pursuing energy decarbonization strategies, including efforts to integrate renewable technologies into its heating systems (Barns et al., 2024). Unlocking the geothermal capacity of the subsurface in this region could provide a scalable and sustainable heating solution to support these initiatives.

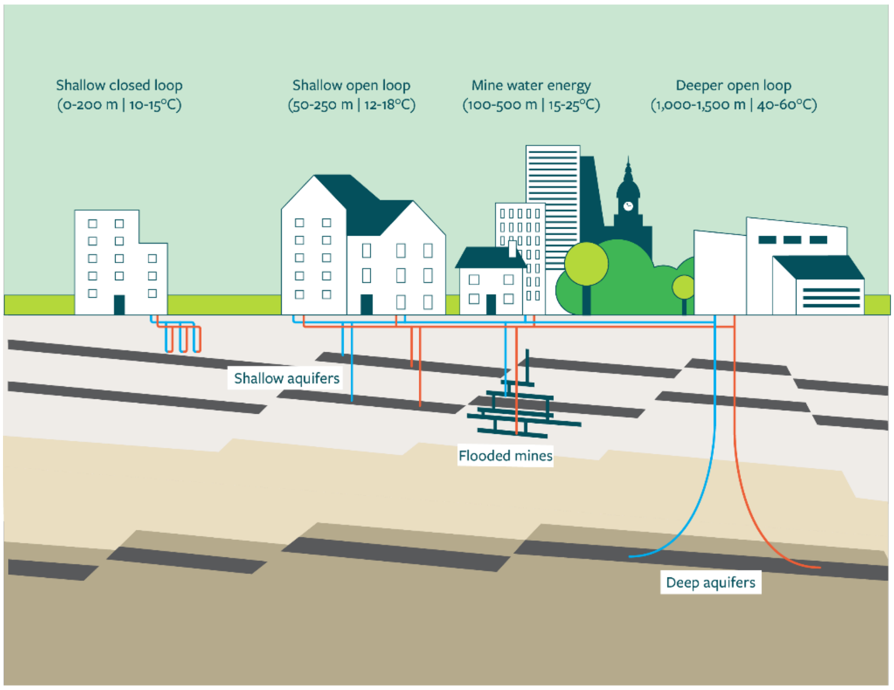

Figure 1 - Shallow subsurface geothermal solutions.

The aim of this study is to evaluate the geothermal potential of the subsurface in Leeds, focusing on depths up to 1,000 meters. By combining publicly available borehole data, geological maps, and various geological reports, we seek to build a 3D geological model of Leeds subsurface. The model describes the lateral and vertical distribution of the key aquifers and the coal mine workings, and includes the physical properties (i.e., porosity and density) of the difference geological formations and their thermal structure. It is then used to calculate the heat-in-place and recoverable thermal power underneath Leeds and assess the suitability of open-loop geothermal applications. Section 2 of this paper gives more details of the background geological context, Section 3 details the modelling approach applied, before Section 4 presents the heat-in-place and recoverable heat for different aquifers and mine-water opportunities. Finally, Section 5 explores the significance of the work in terms of resource availability, uncertainty and risks, and routes to implementation before conclusions are presented.

By using Leeds as a case study, this research contributes to augmenting knowledge on urban geothermal energy potential. The results aim to inform policy decisions, urban planning, and the integration of sustainable low-carbon energy systems, providing a blueprint for other cities to follow in their transition to sustainable energy systems.

2. Leeds Geothermal Context

2.1. Geology

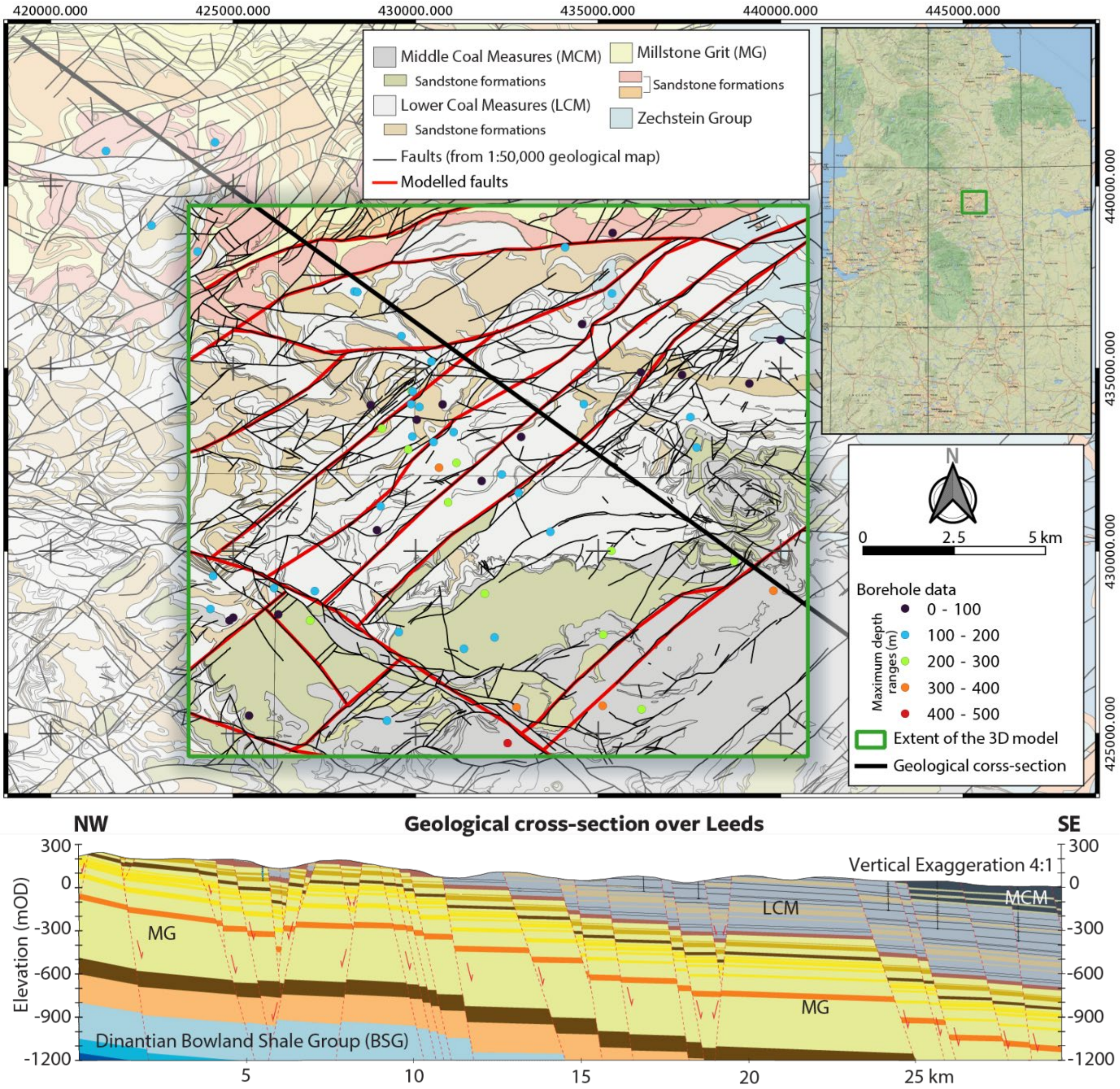

Figure 2 - Map of the study area showing the bedrock geology (BGS, 1998, 2000, 2003a, 2003b)*, the location of the boreholes used to build the geological model, and a NW-SE geological cross-section across the Leeds' area.*

Leeds, located in West Yorkshire, has a diverse geological landscape where Carboniferous to Quaternary rocks are exposed (Figure 2). The bedrock geology primarily consists of Carboniferous rocks, including the Millstone Grit and Coal Measures, overlain in parts by Permian formations and capped by Quaternary superficial deposits(Lake et al., 1992; BGS, 1998, 2000, 2003a, 2003b; Cooper and Gibson, 2003).

The Carboniferous Millstone Grit, outcropping in the northwest, comprises interbedded sandstones and mudstones, forming prominent ridges and escarpments. These sandstones are well-exposed and often contain cross-bedded structures indicative of fluvial and deltaic sedimentation during the Namurian. In contrast, the overlying Coal Measures to the south consist of alternating sequences of mudstone, siltstone, sandstone, and coal, deposited in deltaic and shallow-water environments during the Westphalian. These strata include the economically significant coal seams that historically were mined throughout the region.

Permian strata, particularly the Cadeby Formation (formerly Lower Magnesian Limestone), dominate the eastern part of the Leeds area. This formation comprises dolomitic limestone interbedded with mudstone and gypsum, forming eastward-dipping escarpments. The transition to the Permian was marked by arid conditions, and the subsequent marine transgression deposited the Zechstein Group evaporites and dolomites.

The Quaternary deposits are made of glacial and post-glacial deposits. Thick glacial tills, and sands and gravels are prevalent in the northeast, often reworked by fluvial processes, forming terrace and floodplain deposits in the Aire Valley.

Structurally, the region is affected by major basement structures that are expressed in the surface geology (Figure 2). The region sits in the southern part of the Harrogate Basin, which formed by crustal extension during the Carboniferous, leading to the deposition of the thick carboniferous sedimentary sequences. They thin in the north over the Leeds monocline, thicken in the south, and are segmented by basement-rooted faults (Cooper and Gibson, 2003). These features play a significant role in the region's aquifer distribution, groundwater flow, and geothermal potential.

2.2. Aquifers

The shallow (upper 1000 m) subsurface geology of the Leeds region is mostly made of Westphalian Coal Measures and Namurian Millstone Grit formations, which are classified as minor aquifers, according to their geological heterogeneity and localized significance (Jones et al., 2000). Although shale and clay dominated, they include discrete sandstone units that can support localized groundwater flow. Sandstone fabrics are generally closely packed with quartz overgrowths and pressure welding resulting in low intergranular porosity (ca. 10 to 15%; Jones et al., 2000). The permeability is however varying according to the degree and type of cementation, and fluid migration can be enhanced through fractures and joints. Porosity and permeability generally decrease with depth due to overburden loading, compaction, and increased cementation. However, weathering at shallow depths commonly increases both porosity and permeability, particularly in arenaceous strata (Jones et al., 2000).

The subsurface geology of the Leeds region includes some major aquifers, like the upper Permian Magnesian Limestone and the Early Carboniferous Limestone (Allen et al., 1997). These will not be investigated in this work because they are either too shallow with not enough heat, like the Magnesian Limestone (< 50 m deep) which intersects the surface in the east

(Figure 2), or too deep and poorly constrained by the legacy data, like the Lower Carboniferous Limestone (> 900 m deep) (Pharaoh et al., 2021).

2.3. Mine workings

About 75 billion m^3 of coal was removed in the UK, mostly of Carboniferous age (Farr and Busby, 2021). This legacy of coal mining activity resulted in extensive flooded mine workings, characterized by enhanced permeability and connectivity, ideal for low-enthalpy geothermal energy extraction and heat storage. The Coal Authority estimated that the UK has around 2.2 GWh of heat stored in its flooded mines (Adams et al., 2019), which can be exploited using technologies such as open-loop and closed-loop ground source heat pumps. Convective heat flow within mine water networks, bringing warmer water from deeper levels to the surface, and the exothermic pyrite oxidation reaction further enhance their geothermal potential (e.g., Banks et al., 1996). The proximity of these mines to urban centres reduces the cost and complexity of connecting them to heating networks, presenting a practical and renewable solution for meeting the UK's decarbonization goals (Rattle et al., 2020; Paraskevopoulou et al., 2025). Additionally, mine water systems face little competition for use, as the water is generally unsuitable for potable or industrial purposes. Several existing UK open-loop case studies, such as those at Caphouse Colliery in Yorkshire (Burnside et al., 2016) and Shettleston in Scotland (Banks et al., 2009), demonstrate the feasibility of mine water heating systems. Thus, mine water geothermal systems could play a key role in decarbonizing heating, particularly in former coalfield regions like Leeds, where significant geothermal opportunities remain untapped.

3. Modelling approach

The following sections sets out how geological modelling has been integrated with aquifer properties and subsurface temperature estimates to quantify the available subsurface thermal energy for the Leeds region.

3.1. Workflow

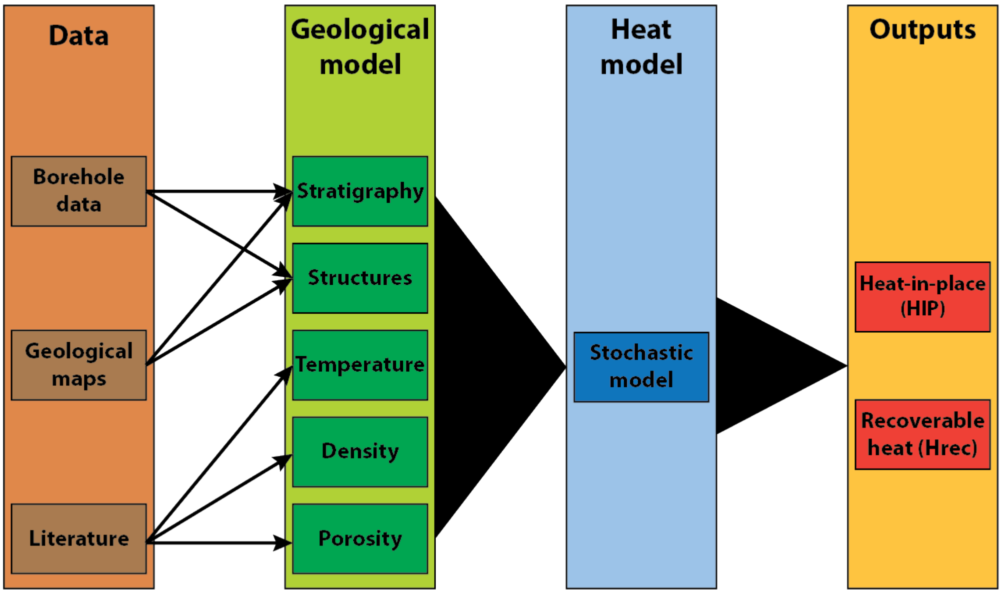

Figure 3 - Subsurface characterization and geothermal resource modelling workflow.

The workflow used in this study is summarized in Figure 3 and consists of the following key steps:

1. **Data acquisition**: geological maps, borehole data, and literature sources were compiled.
2. **Geological model development**: stratigraphy, structural features, subsurface temperature, density, and porosity were integrated into a 3D geological model.
3. **Geothermal potential estimation**: Both deterministic and stochastic models were applied to assess Heat-in-place (HIP) and recoverable thermal power (Hrec).

This workflow ensures a systematic and reproducible approach to evaluating the geothermal potential of the Leeds subsurface, supporting future low-carbon heating initiatives.

3.2. Datasets

The assessment of geothermal potential in the Leeds area was conducted using multiple geological data sources. These include:

1. **Geological maps**: bedrock geology at a 1:50,000 scale was obtained from the British Geological Survey's (BGS) GeoIndex Onshore portal (*https://www.bgs.ac.uk/map-viewers/geoindex-onshore/*) (Figure 2). These maps provide spatial distribution of the various geological formations relevant to building the geological model.
2. **Borehole data**: 66 legacy boreholes, including lithostratigraphic information with maximum depths ranging between 40 and 405 m, were acquired from the UK Onshore Geophysical Library (*https://ukogl.org.uk/*) (Figure 2). These data were first quality controlled, then used to infer the distribution of the main geological formations at depth.
3. **Underground working**: this dataset identifies areas where coal has been mined under the surface and was obtained from the EDINA Digimap online portal (https://digimap.edina.ac.uk/). It provides information about the spatial distribution of the worked coal seams, their thickness, depth, strike, and dip (Figure 4).
4. **British geological survey reports**: published BGS reports and technical documents (e.g., Lake et al., 1992; Jones et al., 2000) provided supplementary information on regional stratigraphy and aquifer characteristics, helping in refining the geological model and the physical properties (ca. density and porosity) of the geological formations.

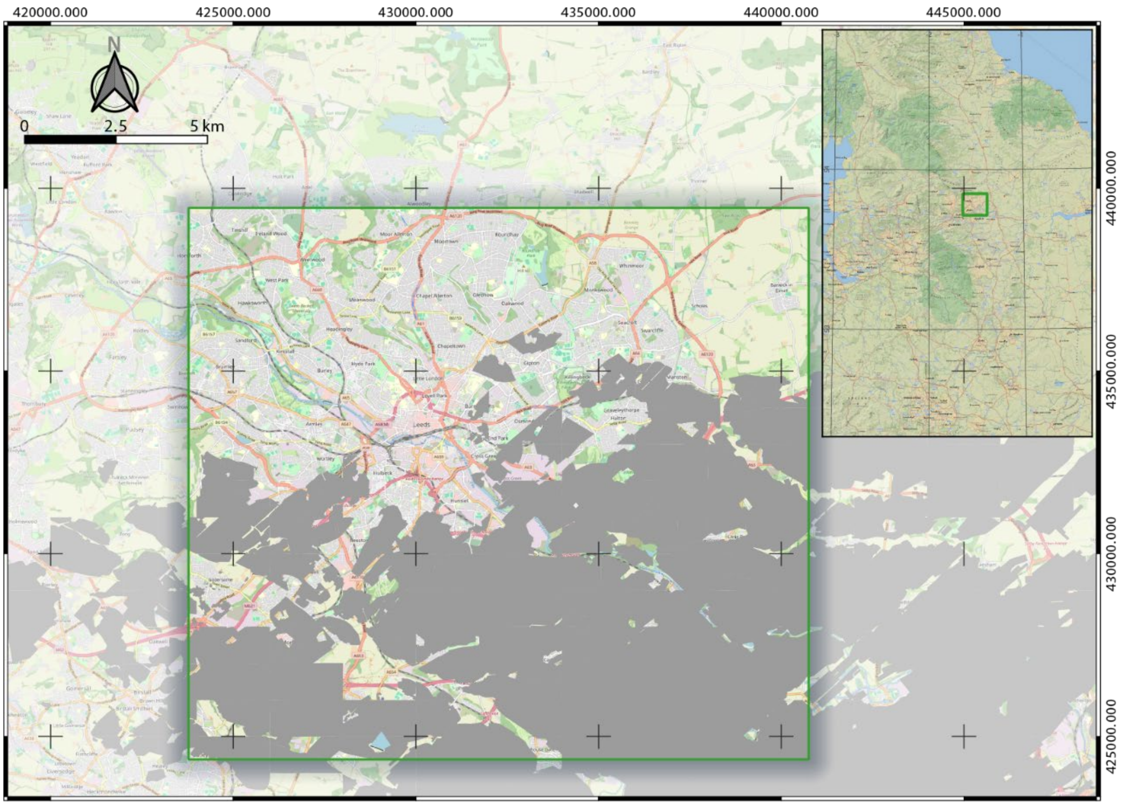

Figure 4 - Map of the Leeds area showing the spatial distribution of underground workings.

3.3. Geological model

A 3D geological model was constructed in Leapfrog, a geological modelling software (Seequent, 2024), using borehole data, geological maps, and published literature.

Geological maps of the Leeds region show mostly upper Carboniferous strata, shallowly dipping (up to 5°) towards the SE, and unconformably overlain by the Permian Rotliegend Group, which outcrops in the east (Figure 2; Cooper and Gibson, 2003). The upper Carboniferous strata consist of the Wesphalian Middle Coal Measures (Westphalian B) and Lower Coal Measures (Westphalian A), conformably overlying the Namurian Millstone Grit Group, which outcrops in the north (Figure 2; Cooper and Gibson, 2003).

The Coal Measures comprise cyclic sequences of interbedded mudstone, siltstone and sandstone with thin (<4 m thick) beds of coal, seatearth and ironstone (Cooper and Gibson, 2003). The mudstone is mostly micaceous, either planarly laminated or massive, and gradually pass into siltstone, which shows ripple cross-lamination and parallel lamination. The sandstones are generally fine-grained with subangular to subrounded quartz and feldspar grains with variable mica content. They show planar lamination, cross-lamination with climbing ripples, and lenticular bedding (Cooper and Gibson, 2003). The coal beds are laterally continuous at the scale of the study area, but can show lateral variations in terms of thickness, composition and number of seams. The sandstone layers within the Coal Measures typically have low to moderate matrix porosity (often <10%) and permeability values that are generally enhanced only where fracture networks are developed (Jones et al., 2000). Groundwater flow in these aquifers is highly heterogeneous and mainly fracture-controlled, resulting in moderate to low flow rates, particularly in deeper units.

The Millstone Grit Group also consists of interbedded mudstone, siltstone and sandstone. Unlike the overlying Coal Measures, the sandstone formations are made mostly of medium to coarse feldspathic grains. The coarser textures imply generally higher permeability and porosity values than in the Coal Measures, particularly in the more massive channel sandstones, which may support more consistent groundwater flow (Jones et al., 2000). However, permeability is still highly variable, and effective fluid flow may remain strongly dependent on fracture networks and the degree of diagenetic cementation.

The Leeds area sits on the southern prolongation of the Harrogate Basin, which is bounded in the north by the Craven Fault and was created in an extensional regime during the early Carboniferous (Kirby et al., 2000). This led to the deposition of a thick sequence of lower Carboniferous strata (up to 3 km), currently preserved underneath the partially exposed upper Carboniferous units. During late Carboniferous times, the extension ceased and basement structures became inactive, leading to a deposition of uniformly thick Namurian (i.e., Millstone Grit) and Westphalian (i.e., Coal Measures) sedimentary sequences (Cooper and Gibson, 2003). By the end of the Carboniferous, the area experienced shortening tectonics due to the Variscan Orogeny and the closure of the Rheic Ocean (Kroner et al., 2018). This led to the reactivation and inversion of the extensional basin structures, and the development of folds that controlled the deposition of the subsequent Permian units and produced an eastward tilting of the area east of the Pennines (Cooper and Gibson, 2003). The faults affecting the area show mostly a net normal displacement with two major trends, northwest and southwest (Figure 2). These faults can potentially act as conduits or barriers to groundwater flow depending on their fill and connectivity. Thus, they are likely to exert a strong control on the geothermal systems by controlling subsurface heat and fluid transport.

The stratigraphic and structural architecture of the study area was simplified for the purpose of this work. Thus, the constructed stratigraphic model captures only the main sandstone formations of the Coal Measures and Millstone Grit groups (see Table 1), and do not differentiate between mudstone and siltstone beds. The coal beds of the Coal Measures are used as markers to correlate the sandstone formations between the boreholes. While the structural model consists of 15 faults (Figure 2) with a standard dip of 60° and varying dip directions derived from the geological maps (BGS, 1998, 2000, 2003a, 2003b).

Table 1 - Modelled sandstone formations and their thickness range in the Leeds region (Cooper and Gibson, 2003).

<table>
<tr><th>Stratigraphic groups</th><th colspan="2">Sandstone formations/aquifers</th><th>Thickness (m)</th></tr>
<tr><td rowspan="2">Middle Coal Measures (MCM)</td><td colspan="2">Horbury Rock (HR)</td><td>0 – 30</td></tr>
<tr><td colspan="2">Thornhill Rock (TR)</td><td>0 – 28</td></tr>
<tr><td rowspan="2">Lower Coal Measures (LCM)</td><td colspan="2">Slack Bank Rock (SBR)</td><td>0 – 38</td></tr>
<tr><td colspan="2">Elland Flags (EF)</td><td>0 – 48</td></tr>
<tr><td rowspan="4">Millstone Grit (MG)</td><td rowspan="3">Upper Millstone Grit aquifer (UMG)</td><td>Rough Rocks & Rough Flags (RR)</td><td>15 – 35</td></tr>
<tr><td>Guiseley Grit (G)</td><td>0 – 26</td></tr>
<tr><td>East Carlton Grit (EC)</td><td>16 – 24</td></tr>
<tr><td></td><td>Lower Follifoot Grit (LFG)</td><td>22 – 48</td></tr>
</table>

	Lower Millstone Grit aquifer (LMG)	Warley Wise Grit (WWG)	40 – 150
		Pendle Grit (PG)	127 – 255

3.4. Underground working model

Underground workings are mostly found in the southern half of the study area (Figure 4). The underground working dataset indicates that the worked coal seam depths range between < 1 and 490 m below ground and worked thicknesses range between 1 and 4 m. The estimated total volume of extracted coal is about 412 million cubic metres. The dataset, identifying the spatial distribution of the worked coal seams, their thickness, depth, strike, and dip, was used to build a 3D model of the underground working in Leapfrog.

It is noteworthy to mention that the mine water model does not include mine infrastructures (e.g., shafts, galleries), which should substantially increase the estimated geothermal resources linked to the abandoned mines.

3.5. Temperature model

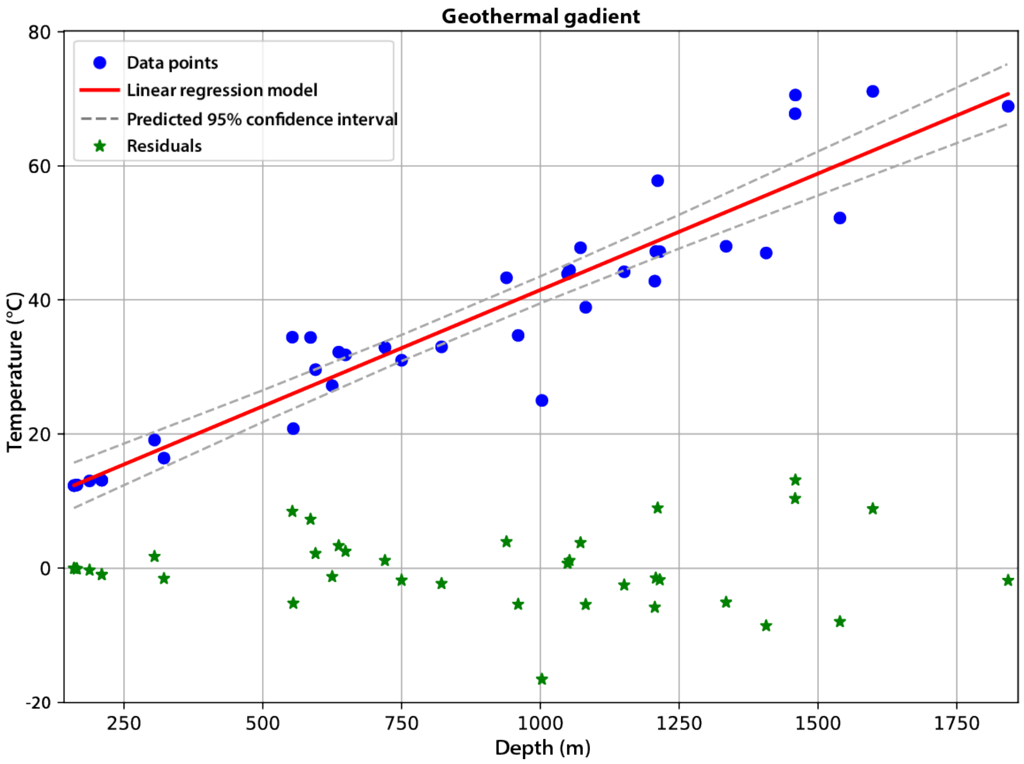

Figure 5 - Borehole temperature data and geothermal gradient derived by linear regression.

Borehole temperature data from 29 boreholes, located near the study area, were used to assess the subsurface geothermal gradient (Figure 5). Linear regression analysis of the data shows a strong temperature-depth relationship with a coefficient of determination (R^2) value of 0.89:

$$T = 0.0347 \times Z + 6.788$$

where T is temperature (°C) and Z is depth (m) below ground.

The obtained geothermal gradient of 34.7 °C/km is relatively high and consistent with the elevated surface heat flow density estimates for the Yorkshire area (70-80 mW/m^2; Busby, 2010).

3.6. Geothermal resource model

Geothermal resource assessment in the Leeds region is calculated stochastically, using the open-source software 3DHIP, which was developed by Piris et al. (2021). It is based on the USGS volumetric Heat-in-Place method (Muffler and Cataldi, 1978; Garg and Combs, 2015), which estimates:

1- the Heat-In-Place (HIP, in Joules), the total thermal energy stored in the subsurface, considering rock porosity, density, specific heat, and the thermal gradient, according to the following equation,

$$HIP = V \times [\varphi \times \rho_F \times C_F \times (1 - \varphi) \times \rho_R \times C_R] \times (T_r - T_i)$$

where V is the reservoir volume (m^3), φ is the porosity, ρ_F and ρ_R are fluid and rock densities (kg/m^3), respectively, C_F and C_R are fluid and rock specific heat capacities (kJ/kg. °C), respectively, T_r and T_i are reservoir and re-injection temperatures (°C), respectively;

2- the Recoverable Heat (Hrec, in kW), an estimate of the producible thermal power (in kilowatts),

$$Hrec = \frac{HIP \times Ce \times R}{Tlife \times Pf}$$

assuming a conversion efficiency of the heat exchanger (Ce), a recovery factor (R), the expected lifetime of a geothermal project (Tlife), and the proportion of time a geothermal plant is likely to be operating (plant factor, Pf).

HIP and Hrec were modelled for four potential reservoirs:

- the Eland Flag aquifer, found within the Lower Coal Measures unit,
- an upper Millstone Grit reservoir, comprising the Rough Rocks, Rough Rock Flags, Guiseley Grit, and East Carlton Grit sandstone formations,
- a lower Millstone Grit reservoir, made of the deep Warley Wise Grit and Pendle Grit sandstone formations,
- and the mine water, related to the coal workings of the Middle and Lower Coal Measures units.

The volumes of these resources were determined from the 3D geological model in Leapfrog using a discretization (x, y, z) of 200*200*10 m for the aquifers and 200*200*0.1 m for the mine water geothermal resources..

Other modelling input parameters and corresponding probability distributions are listed in Table 2.

Table 2 - Input parameters used for heat-in-place and recoverable heat power modelling. The probability distribution of each parameter is either normal (mean value ±standard deviation) or triangular (minimum – mode –

maximum). Sources: a (Jones et al., 2000)*; b* (Lake et al., 1992)*; c* (Taylor and Spears, 1970)*; d* (Jones et al., 2023)*; f* (Williams, 2007)*; g* (Piris et al., 2021)*; h* (Strezov et al., 2004)*; i* (Xiong et al., 2020).

Input parameter	Values			
	EF	UMG	LMG	Mine water
Porosity (φ, fraction)	0.07 – 0.12 – 0.20 [a]	0.06 – 0.14 – 0.23 [a]		0.05 – 0.30 – 0.50
Rock density (ρ_R, kg/m³)	2260 – 2415 – 2570 [b]			2000 ± 20 [c]
Rock specific heat capacity (C_R, kJ/kg.°C)	0.86 ± 0.01 [d, i]			1.40 ± 0.01 [h]
Fluid Density (ρ_F, kg/m³)	1040 ± 5 [d]			
Fluid specific heat capacity (C_F, kJ/kg.°C)	3.8 ± 0.1 [d]			
Reinjection Temperature (T_i, °C)	8 [e]			
Recovery factor (R, fraction)	0.05 – 0.10 – 0.20 [f]			
Conversion efficiency (Pf, fraction)	0.85 [g]			
Plant lifetime (Tlive, years)	30 [g]			

Subsurface temperatures and associated uncertainty for each aquifer and the mine workings were derived from the temperature-depth linear regression model and the predicted 95% confidence interval, respectively (Figures 5 and 6). The modelling results for each reservoir are based on 10,000 simulations and are expressed in terms of probabilities. P10, P50, and P90 correspond to the 10^{th}, 50^{th}, and 90^{th} percentiles of the calculated cumulative distribution function, respectively indicating higher confidence estimates (Piris et al., 2021).

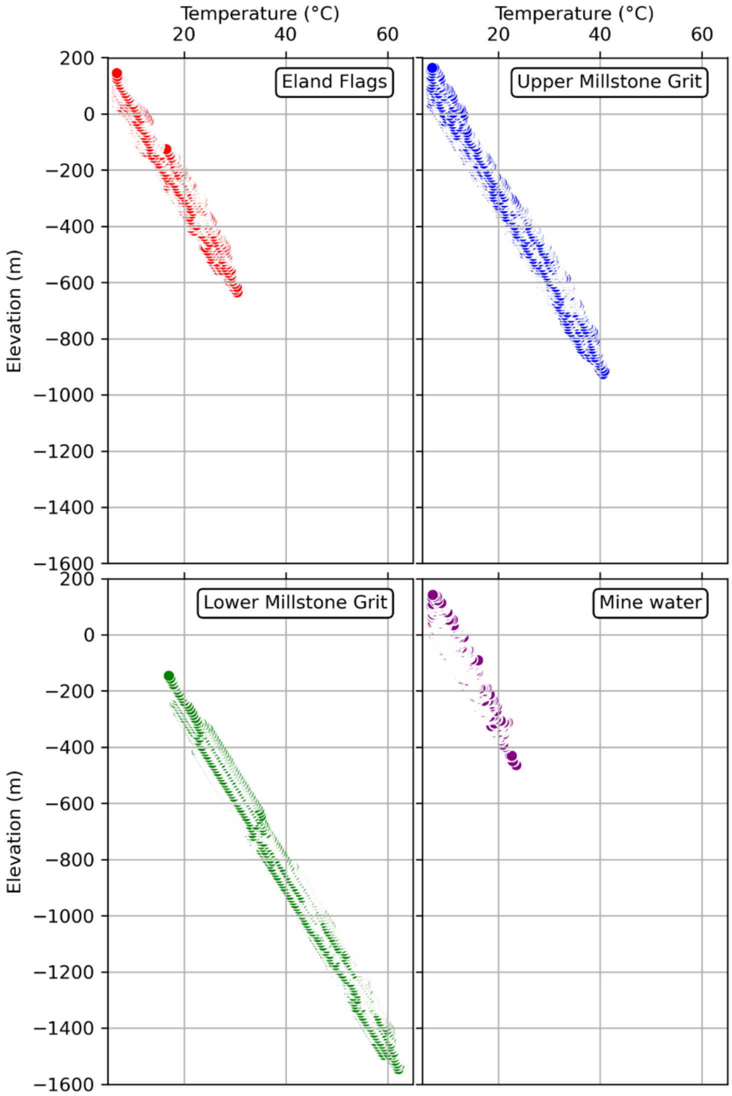

Figure 6 – Temperature distribution within the modelled geothermal reservoirs. Elevation is calculated with respect to the mean sea-level and temperatures is derived from the modelled temperature-depth equation.

4. Results

The geothermal reservoirs modelled in this study, Elland Flags (EF), Upper Millstone Grit (UMG), Lower Millstone Grit (LMG), and abandoned mine workings, display distinct spatial and thermal characteristics across the Leeds subsurface.

The Elland Flags sandstones (Figure 7) occur at shallow to intermediate depths (ca. 200–650 m) with a thickness ranging between 20–60 m. The top reservoir temperature spans from approximately 8 to 30 °C, reflecting its relatively shallow position. In contrast, the Upper Millstone Grit (Figure 8), which comprises three sandstone aquifers, is deeper (top depths from ca. 0–850 m), with reservoir temperatures ranging from 8 to 36 °C, and a thickness that is generally between 60 and 80 m in most locations. The Lower Millstone Grit (Figure 9), which consists of two sandstone aquifers, is the deepest reservoir, with the top encountered at depths between 250–1300 m, where predicted temperatures reach 16–52 °C. This unit is also the thickest among the three sandstone aquifers, often exceeding 250 m in total thickness.

Mine water resources (from flooded coal workings) are mainly located at shallower depths (< 500 m), predominantly in the southern half of the study area (Figure 4), where historical coal mining activity was concentrated. These zones represent volumetrically smaller but strategically significant low-temperature geothermal targets.

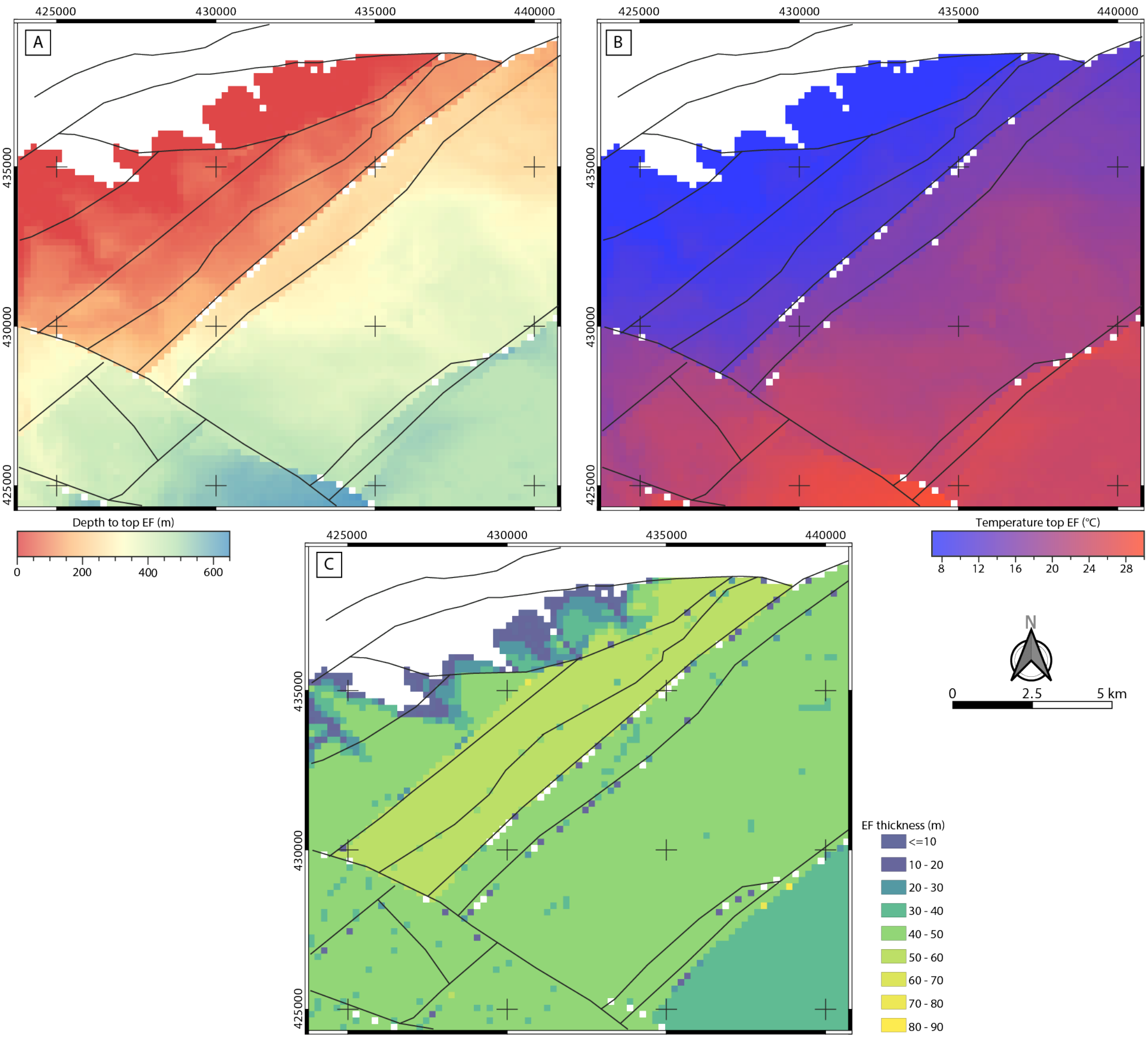

Figure 7 - Characteristics of the Eland Flags geothermal reservoir. A: Depth to top EF. B: Temperature at the top of EF. C: Thickness of the EF.

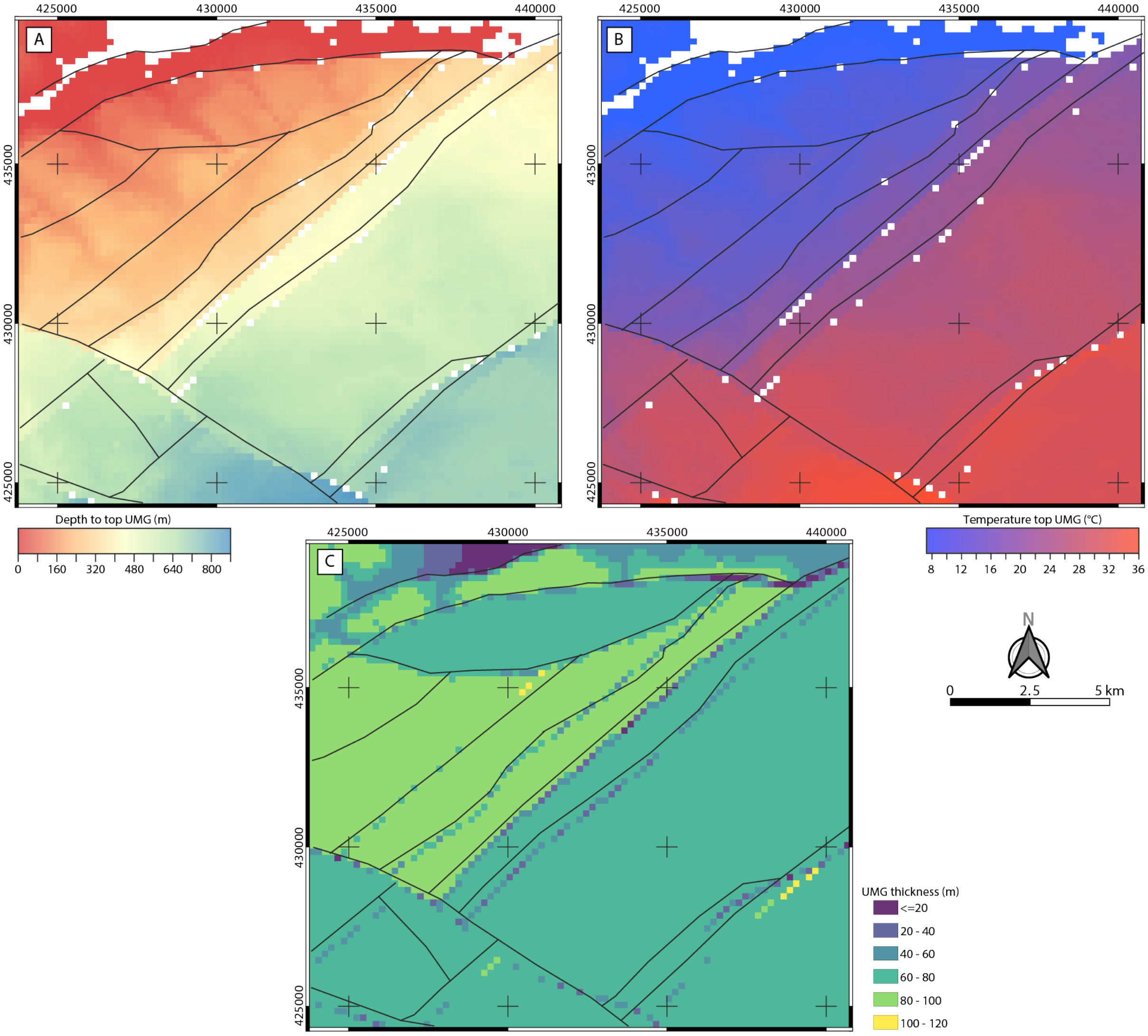

Figure 8 - Characteristics of the Upper Millstone Grit (UMG) geothermal reservoir. A: Depth to top UMG. B: Temperature at the top of UMG. C: Thickness of the UMG.

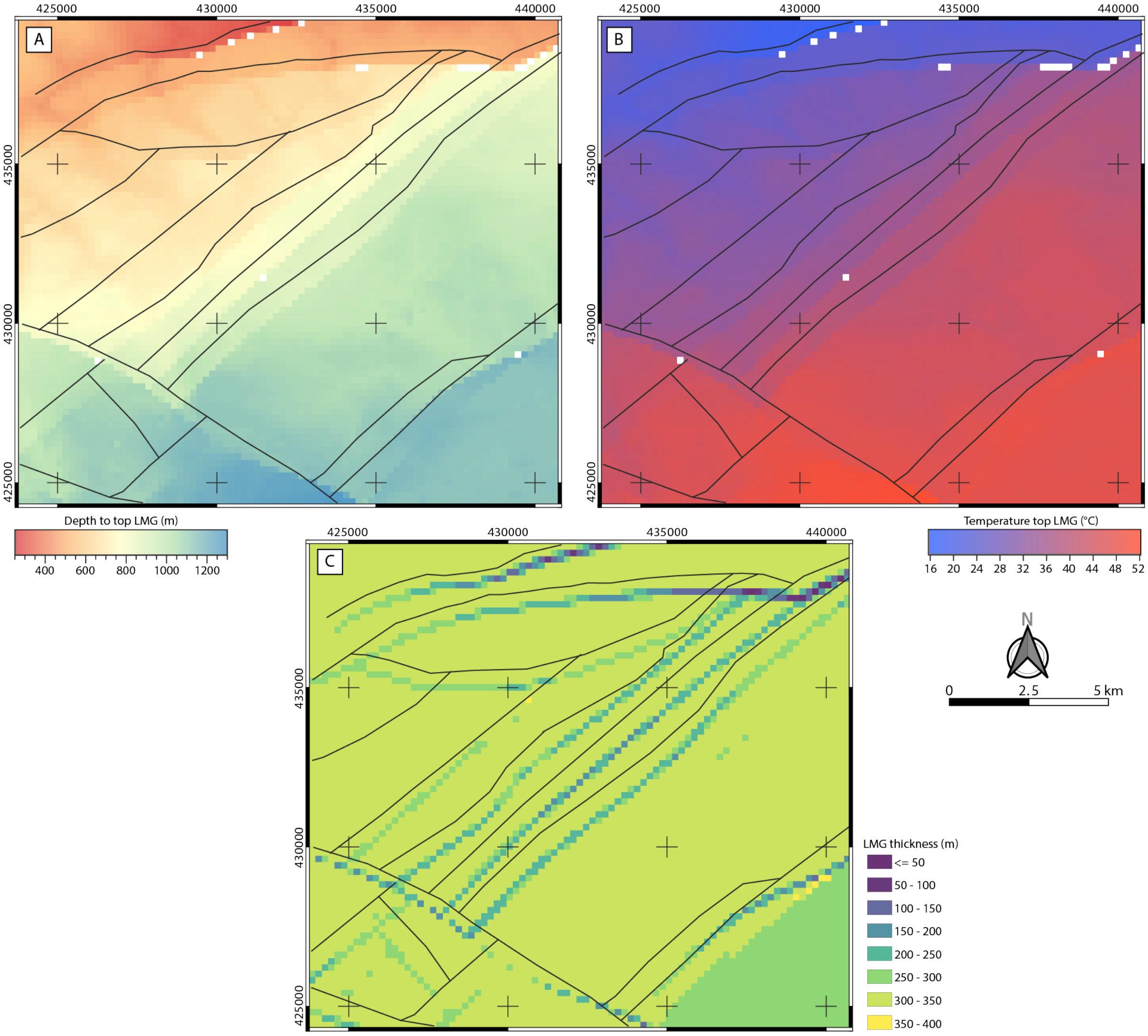

Figure 9 - Characteristics of the Lower Millstone Grit (LMG) geothermal reservoir. A: Depth to top LMG. B: Temperature at the top of LMG. C: Thickness of the LMG.

Table 3 - Total heat-in-place (HIP, GWh) and recoverable heat power (Hrec, kW) for the different geothermal reservoirs in the shallow subsurface of Leeds.

		Aquifers			
		EF	**UMG**	**LMG**	**Mine water**
Depth range (km)		0 – 680.2	0 – 1,040.7	292 – 1518.2	0 – 641.5
Temperature range (°C)		6.8 – 30.4	6.8 – 40.7	16.9 – 62.2	6.8 – 23.5
Volume (km³)		8.8	17.8	74.1	0.36
HIP (GWh)	P10	51,102.8	17,5869.4	1,723,891.7	1,205.6
	P50	49,033.3	16,8713.9	1,643,530.5	1,147.2
	P90	46,966.7	17,5869.4	1,576,563.9	1,091.7
Hrec (kW)	P10	28,109.9 [21,623]	94,166.6 [72,435]	901,379.0 [693,368]	720.9 [555]

[# homes equivalent]	P50	17,858.7 [13,737]	61,948.4 [47,652]	621,802.0 [478,309]	401.3 [309]
	P90	10,430.9 [8,023]	38,673.9 [29,749]	410,664.0 [315,895]	168.1 [130]

Using the stochastic 3DHIP model (Piris et al., 2021), total thermal energy stored in each reservoir (HIP) and its recoverable portion (Hrec) were calculated. Table 3 summarizes the probabilistic results for P10 (low confidence), P50 (median), and P90 (high confidence) estimates.

- The Lower Millstone Grit (LMG) reservoir emerges as the most significant geothermal target, with a median HIP of 1,643,530.5 GWh and a median recoverable heat output (Hrec) of 622 MW. Its large volume and elevated temperatures contribute to its elevated geothermal potential.
- The Upper Millstone Grit (UMG) also shows substantial geothermal potential, with 16,8713.9 GWh of HIP and 62 MW of Hrec at the P50 level.
- The Elland Flags (EF) reservoir presents more modest values, with a median HIP of 49,033.3 GWh and a recoverable heat power (Hrec) of 18 MW.
- The mine water system, despite its limited reservoir volume, yields a reasonable P50 HIP of 1,147.2 GWh and 401 kW of recoverable heat power (Hrec), highlighting its potential for localized heating applications, particularly via open-loop systems.

Figure 10 presents the spatial distribution of P50 heat-in-place (HIP per km^2) across the four geothermal targets. The Lower Millstone Grit displays the broadest and most thermally compelling footprint beneath Leeds, especially in the central and southern parts of the city. The Upper Millstone Grit and Elland Flags also exhibit good thermal potential in southern and western zones, suggesting clustered zones of opportunity for geothermal development. The mine water geothermal resource is more spatially restricted but corresponds closely with historical mining zones, offering exciting opportunities for re-use of legacy infrastructure.

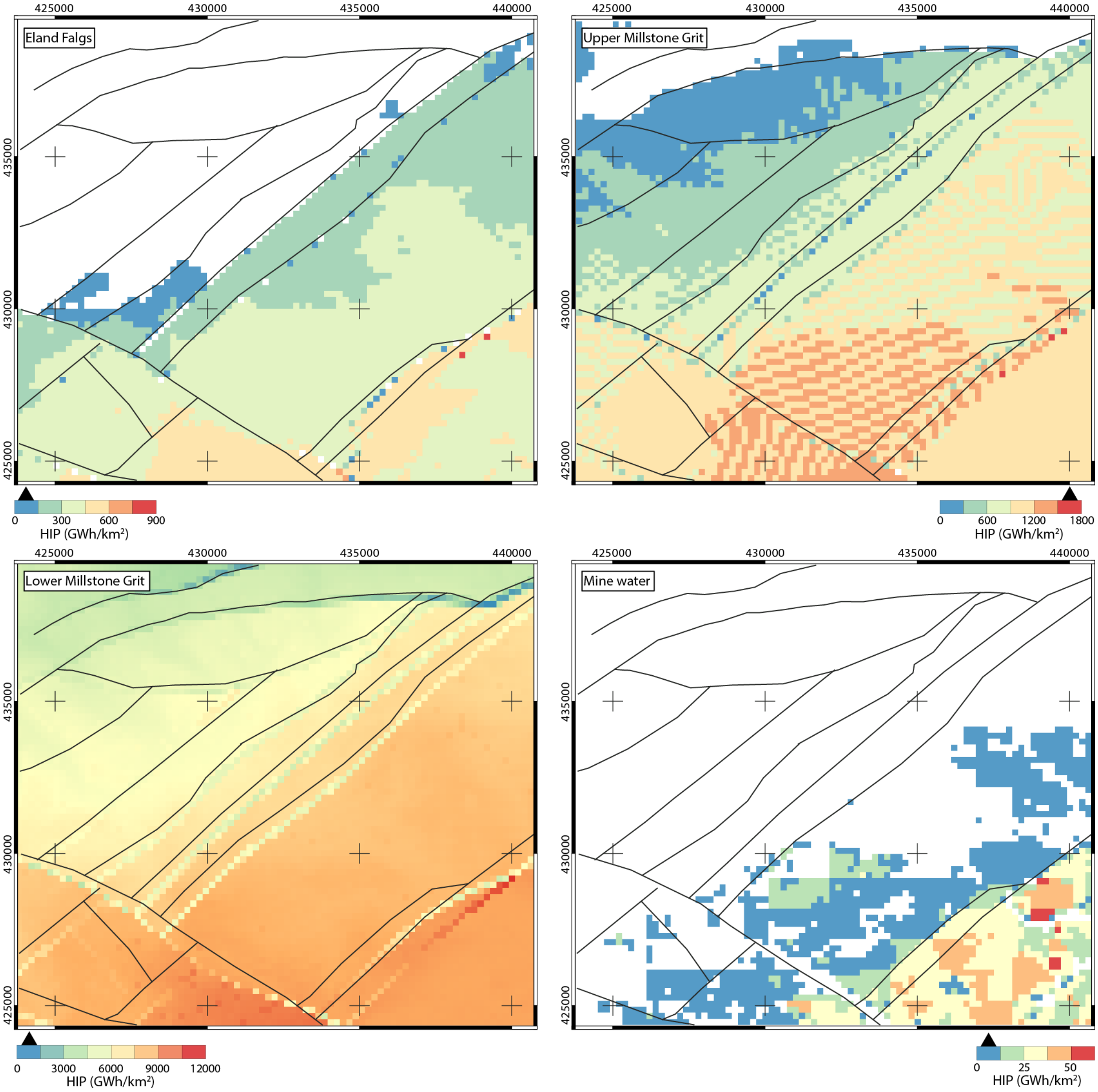

Figure 10 - Heat-in-place (HIP, GWh/km²) distribution for the Eland Flags, Upper Millstone Grit, Lower Millstone Grit, and mine water, based on the P50 stochastic model.

5. Significance and implementation

5.1. Geothermal resource and regional heating potential

Our results demonstrate that Leeds' upper 1,000 m of the subsurface holds considerable geothermal energy potential. The total median heat-in-place (HIP) across the four reservoirs evaluated (Elland Flags, Upper Millstone Grit, Lower Millstone Grit, and mine water) exceeds 1833333 GWh, with a combined recoverable heat output (Hrec) of over 700,000 kW at P50 levels. These figures are highly significant in the context of regional heating needs. Assuming an average domestic heating demand of approximately 11,500 kWh/year per household (Ofgem, 2025), the recoverable geothermal energy could theoretically support the space and water heating needs of over 540,000 homes for 30 years in the Leeds area, which exceeds the total number of residential properties in the entire Council of 362,780 (as of 2021 census; Leeds City Council, 2021). This positions geothermal energy as a viable contributor to Leeds' net-zero ambitions and supports broader policy efforts around decarbonising domestic and public heating systems.

5.2. Uncertainty in resource estimates

Uncertainty is inherent in subsurface modelling and resource assessment, and this study has incorporated probabilistic methods to explicitly address it. The differences between P10 and P90 values, particularly for the Lower Millstone Grit, ranging from 901 to 410 MW, respectively, highlight how sensitive recoverable heat estimates are to variations in porosity, aquifer thickness, and geothermal gradient. Particularly, temperature data is interpolated from nearby boreholes rather than directly measured at depth underneath the study area, which adds a layer of uncertainty. Additionally, the constructed 3D geological model does not account for finer-scale lithological heterogeneity and full structural complexity of the subsurface that may locally enhance or impede heat and fluid flow.

A critical yet unquantified component of uncertainty relates to groundwater flow rates, which are essential for the successful operation of open-loop systems and Aquifer Thermal Energy Storage (ATES). Achieving sustainable extraction and reinjection rates is a prerequisite for thermal performance but has only been demonstrated at a few locations in Leeds. Recent test results from the University of Leeds geothermal campus project show promising rates in the fractured Elland Flags sandstone; however, more data are needed from the different aquifers and different depths. Historical BGS data from the Lower and Middle Coal Measures suggest flow rates rarely exceeding 1 l/s, although exceptionally a yield of 7.5 l/s was obtained in favourable sandstones (Jones et al., 2000), though this is likely to vary significantly with fracture distribution and connectivity, and well design. On the other hand, abandoned mine workings workings have showed flow rate up to 250 l/s, although flow rates tended to reduce asymptotically (Jones et al., 2000).

These uncertainties have direct implications for project viability, risk, and cost. While deeper formations such as the Lower Millstone Grit appear to offer substantial recoverable heat, their exploitation involves greater drilling depths, higher capital costs, and greater uncertainty regarding reservoir performance. In contrast, shallower systems, such as those targeting mine water or upper sandstone horizons, may be easier to characterise and tap into, which often results in lower levelized costs of heat, owing to reduced drilling, permitting, and operating risks (ARUP, 2025). As such, resource potential must be weighed against risk-adjusted cost profiles when considering system design and investment priorities.

Together, these uncertainties reinforce the importance of targeted subsurface characterisation, including thermal logging, in-situ hydraulic testing, and urban seismic imaging, particularly for deeper or poorly constrained zones. Reducing these knowledge gaps, amongst other, is essential for de-risking geothermal developments and for guiding where early investment can yield the greatest impact.

5.3. Pathways for implementation: linking with heat networks

Spatial analysis of HIP per km^2 (Figure 10) shows that high thermal potential zones align well with urbanised areas, particularly in central and southern Leeds. These hotspots are highly suitable for integration into district heating networks, especially where demand density is high and land availability for infrastructure is constrained. This supports findings from Barns et al. (2025, in this issue), who identify zoning and planning policy as essential levers for deploying low-carbon heat systems. Priority implementation zones could include areas with overlapping geothermal resource and social heat demand, such as council housing clusters or public buildings with consistent year-round heat use. Cross-referencing these geothermal resource maps with socio-economic data and existing network infrastructure, can provide a framework for targeted roll-out of shared-loop or district-scale ground-source heat pump systems.

5.4. Barriers to realisation

Geoscientific barriers:
Current limitations in subsurface data, particularly at depths >500 m, pose a key challenge to reducing uncertainty and de-risking investment. The existing model was constructed using sparse legacy borehole records and regional generalisations of thermal gradients. Enhancing model reliability will require urban seismic campaigns, new exploratory drilling, and development of high-resolution hydrogeological models to better predict flow and thermal transport properties across the identified reservoirs. Improving our understanding of fracture networks, mine connectivity, and lithological variations is especially critical for assessing deliverability and designing open-loop systems.

Non-technical barriers:
A range of non-technical factors also constrain the deployment of geothermal project in the UK in general. High upfront capital costs remain the most significant barrier, particularly for open-loop or deep systems requiring advanced and costly infrastructure. The ARUP geothermal energy review (ARUP, 2025) notes that while geothermal heat can be cost-effective over the system lifetime, the lack of suitable funding mechanisms and long payback periods often deter private investors.

Uncertainty in regulation also plays a role, especially for open-loop systems, which must navigate complex permitting processes than closed-loop alternatives. Inconsistencies is subsurface rights management across various regulatory bodies (e.g., Coal Authority, Environmental Agency, local planning authorities) add further delays. Large-scale systems depend on reliable heat offtakers, which often requires integration with heat networks, which may not yet exist in the project area.

Another issue is the need to identify appropriate risk holders for major ground works. With no established model for who owns and manages long-term subsurface risk, whether public authorities, developers, or utilities, project liability remains a grey area slowing progress. Addressing these barriers will require coordinated policy responses that streamline planning, de-risk investment, enable reasonable/shared financial and legal responsibilities across stakeholders.

6. Conclusion

This study provides a broad assessment of the shallow to mid-depth (>1,000 m) geothermal potential beneath the city of Leeds, using a combination of 3D geological modelling, legacy borehole data, and stochastic heat-in-place calculations. Four key geothermal reservoirs were evaluated: the Elland Flags, Upper and Lower Millstone Grit sandstones, and flooded mine workings, representing the most promising subsurface heat sources within the top 1,500 meters.

The results show that Leeds possesses a substantial geothermal resource, with a combined median heat-in-place exceeding 1,833,333 GWh and a recoverable thermal power output of over 700 MW (>500,000 home equivalent). Among the evaluated targets, the Lower Millstone Grit stands out as the most significant contributor, in terms of both stored energy and recoverable power, due to its greater depth, thickness, and temperature. However, this elevated potential is balanced by increased technical and financial risks, including deeper drilling, higher uncertainty in flow rates, and limited local testing. In contrast, shallow aquifers, such as the Elland Flags and Upper Millstone Grit, offer lower geothermal potential but are more accessible, making them attractive for lower-risk geothermal deployment. Mine water systems, while offer a more modest energy resource, their accessibility at shallow depths and near demand centres makes them attractive for decentralised, low-temperature heating schemes. Thus, the development of geothermal must be approached in a risk-adjusted framework, where technical feasibility, economic viability, and confidence in subsurface conditions are carefully weighed against resource magnitude.

This work highlights the strategic potential of geothermal energy to contribute meaningfully to heating decarbonization and energy transition goals in Leeds. The distribution of the estimated geothermal potential aligns with the city's existing urban fabric, which reveals several zones as prime candidates for integration into district or shared-loop heating networks.

However, unlocking this potential will require addressing both technical and non-technical barriers. From a geoscience perspective, reducing uncertainty in reservoir properties, particularly temperature and flow rate, through new data acquisition is essential. On the implementation side, improved policy coordination, clearer permitting pathways, and investment support will be vital to enable deployment at scale.

Overall, this work not only highlights Leeds as a viable candidate for urban geothermal development but also offers a replicable methodology for evaluating geothermal resources in other UK cities. Future research and pilot schemes should focus on translating this potential into action, ensuring geothermal energy plays a central role in the transition toward a resilient, low-carbon urban energy system.

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