

Digging deeper: The influence of historical mining on Glasgow's subsurface thermal state to inform geothermal research



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Abstract: Studies of the former NE England coalfield in Tyneside demonstrated that heat flow perturbations in boreholes were due to the entrainment and lateral dispersion of heat from deeper in the subsurface through flooded mine workings. This work assesses the influence of historical mining on geothermal observations across Greater Glasgow. The regional heat flow for Glasgow is 60 mW m^{-2} and, after correction for palaeoclimate, is estimated as $c. 80 \text{ mW m}^{-2}$. An example of reduced heat flow above mine workings is observed at Hallside ($c. 10 \text{ km SE}$ of Glasgow), where the heat flow through a 352 m deep borehole is $c. 14 \text{ mW m}^{-2}$. Similarly, the heat flow across the 199 m deep GGC01 borehole in the Glasgow Geothermal Energy Research Field Site is $c. 44 \text{ mW m}^{-2}$. The differences between these values and the expected regional heat flow suggest a significant component of horizontal heat flow into surrounding flooded mine workings. This deduction also influences the quantification of deeper geothermal resources, as extrapolation of the temperature gradient above mine workings would underestimate the temperature at depth. Future projects should consider the influence of historical mining on heat flow when temperature datasets such as these are used in the design of geothermal developments.

Supplementary material: Background information on the chronology of historical mining at each borehole location and a summary of groundwater flow in mine workings beneath Glasgow are available at <https://doi.org/10.6084/m9.figshare.c.4681100>

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The catalyst for geothermal exploration worldwide is the need to produce low carbon renewable energy (e.g. [Younger 2015](#)). Following the global oil crisis in the 1970s and in an attempt to guarantee the future supply of energy, geothermal resources in Britain were assessed as a potential alternative for the production of heat and generation of electricity. The hot sedimentary aquifers (HSAs) of the Lower Carboniferous and Upper Devonian sandstones of the Midland Valley of Scotland (MVS) were identified as a potential target resource ([Browne *et al.* 1985, 1987](#); [Downing & Gray 1986](#); [Brereton *et al.* 1988](#)). Despite concluding that a likely exploitable temperature in excess of 60°C could be accessed at a depth of 2.5 km ([Browne *et al.* 1987](#)), the drilling risks and associated expenditure meant that the resource has hitherto remained unexploited.

Renewed interest in the geothermal potential of the MVS has recently emerged and can be attributed to two developments: (1) a focus on renewable heat, instead of electricity, generation and resulting reassessment of the lower temperature resource; and (2) a rigorous reassessment of UK heat flow data to account for the effects of palaeoclimate and topography. Efforts to address the latter have suggested that the UK's potential geothermal resource has been underestimated and that higher temperatures may be found at shallower depths than previously thought ([Westaway & Younger 2013, 2016](#); [Busby *et al.* 2015](#)). Both developments are of particular relevance to Scotland, which is the focus of the current study.

In Scotland, heat accounts for 51% of energy demand ([Scottish Government 2018](#)). The Scottish Government has set a target of producing 11% of heat supply from renewables by 2020. In 2017, only 5.9% of heat demand in Scotland was met from renewable resources ([Scottish Government 2019](#)). Furthermore, in 2017, 24.9% of households in Scotland were considered to be fuel-poor and 7.5% were living in extreme fuel poverty ([Scottish House Conditions Survey 2018](#)). The simultaneous pursuit of energy decarbonization and fuel-poverty alleviation poses a considerable challenge, given that pursuing a low carbon energy strategy is more expensive than retaining the *status quo* where most domestic heating in the UK is achieved through the burning of natural gas ([BEIS 2019](#)). Geothermal energy represents a significant supply, as yet unused, of large-scale renewable heat. As discussed by [Gluyas *et al.* \(2018\)](#), as part of an integrated low carbon energy supply network, geothermal energy could provide a significant contribution to realizing a holistic solution for this important dilemma.

The MVS is host to two potentially significant geothermal resources: insulated groundwater in flooded abandoned mine workings; and HSAs within the Kinnesswood Formation, Knox Pulpit Formation, and laterally equivalent sandstones ([Browne *et al.* 1985, 1987](#); [Gillespie *et al.* 2013](#)). The areas of the MVS where the resource is present encompass the largest cities in Scotland, Glasgow and Edinburgh. The urban development in the MVS has been a legacy of its economic development, mainly fuelled from local coalfields,

exploiting the same sedimentary sequence that contains the geothermal resource. This presents the opportunity of providing geothermal heating to areas of dense urban population and high heat demand.

Within the past decade, significant research has been conducted on the potential geothermal resource in Scotland (Gillespie *et al.* 2013; Scottish Government 2015; Monaghan *et al.* 2017, 2018). Despite the long tradition of coal exploration, and minor oil and gas exploration in the MVS, there is a scarcity of deep onshore boreholes. The hydraulic properties of both the flooded abandoned mine workings and the deeper HSAs remain poorly understood (Ó Dochartaigh *et al.* 2018) and uncertainty still exists regarding the likely temperature that will be accessible.

However, recent work has demonstrated that understanding the flow of heat in the subsurface provides insight into the quantification of the potential geothermal resource in flooded abandoned mine workings and deeper HSAs. Westaway & Younger (2016) assessed various factors that contribute to the behaviour of subsurface thermal energy flows. One such factor, prevalent in Tyneside, is likewise possible beneath the Glasgow area: the entrainment and lateral dispersion of heat through abandoned mine workings. There is also the possibility that upward or downward groundwater flow influences subsurface heat flow. Either of these mechanisms may mean that subsurface temperature measurements may not be representative of the conductive heat flow in the locality.

When assessing the geothermal potential of the MVS, an effort was made to conduct temperature and heat flow measurements in boreholes that were sited in locations free from mine workings (Monro 1983). However, this is not so for all the borehole datasets. For example, in the nineteenth century, Sir William Thomson (Lord Kelvin) measured temperatures in boreholes sunk precisely in order to prospect for coal and ironstone (Thomson 1868; Thomson *et al.* 1868, 1869). While these boreholes were not developed into mine shafts, the locality in which they were drilled may have been extensively mined at the time.

An examination of the 'true' geothermal resource beneath the city of Glasgow is therefore reliant on an understanding of heat transport mechanisms in the subsurface. As a first step, this work investigates the presence and influence of mine workings on borehole temperature measurements in Glasgow.

Westaway & Younger (2016) also assessed the effect of downward propagation of heat from the surface due to global warming, Urban Heat Island (UHI) development and industrial processes. These factors, prevalent in Tyneside, due to the area's industrial heritage, are likewise potentially influential beneath Glasgow. If present, this warming effect would increase the temperature in the subsurface beneath the particular locality. Where relevant, this factor has been noted within this study, although quantitative analysis is outside the scope of this work.

A chronology of mining activity in the vicinity of each of the boreholes was established using material from the Glasgow Archives in the Mitchell Library of the City of Glasgow, the Renfrewshire Archives and the National Records of Scotland. The material examined included: mine entry data obtained from the Coal Authority's Online

Interactive Map (Coal Authority 2018) and the Northern Mine Research Society Online Interactive Map (Northern Mine Research Society 2018); mine abandonment plans; borehole records held by the British Geological Survey (BGS); geological and mining memoirs; and historical maps.

By unravelling the effect of mine workings on the subsurface thermal state, an appraisal of existing geothermal measurements across the city of Glasgow can be made. This enables: (1) a quantification of the potential geothermal resource in the abandoned, flooded mine workings; (2) an assessment of the accuracy of existing subsurface temperature measurements, for example as a precursor to applying corrections to heat flow measurements to account for palaeoclimate and topography (Westaway & Younger 2013); and (3) a more accurate extrapolation of subsurface temperature measurements to greater depths, enabling a quantification of the potential geothermal resource in the underlying HSAs.

This paper is organized as follows: a summary of the bedrock geology of the Glasgow area is presented; boreholes included in the study area, with available temperature and heat flow data, which may be sensitive to the presence of mine workings, are then detailed; an overview of the extent of mineral extraction in the Lanarkshire and Renfrewshire Coalfields, prior to the temperature measurements being made in each borehole, is then presented; and a first-order quantification of the geothermal resource in the mine workings at candidate borehole locations is then conducted.

Geological setting

Underlying central Scotland is the MVS, a WSW–ENE-oriented graben of Devonian–Carboniferous age. The basin is bounded to the north by the Highland Boundary fault and to the south by the Southern Upland fault. It contains an internally complex arrangement of several sedimentary basins and small Lower Paleozoic inliers; which occur in the Lesmahagow area, the Pentland Hills and south Ayrshire (Cameron & Stephenson 1985; Trewin & Rollin 2002). The primary focus of this study is Glasgow and the western MVS (Fig. 1). The greater part of this area is occupied by a wide, gently undulating plain where the city of Glasgow and surrounding conurbation, with large population density and urban development, are located. To the north, the topography rises in the Campsie Fells and Kilpatrick Hills (Fig. 1). To the south, the Beith-Barrhead Hills and Cathkin Braes form analogous high topography, these uplands being in the footwalls of major normal faults of Carboniferous age (Fig. 1).

The lower ground between these major faults is largely underlain by sedimentary and igneous rocks of Carboniferous age, dissected by a complex network of lesser faults (Fig. 1) (Forsyth *et al.* 1996; Hall *et al.* 1998). Detailed in Table 1, this bedrock geology is dominated by cyclical successions of sedimentary rocks, namely the Clackmannan and Scottish Coal Measures groups. These strata consist of sandstones and mudstones, with limestones, coals, ironstones and seatrocks, which were laid down in fluvial and fluviodeltaic environments that were established after the submergence of the underlying Clyde Plateau Volcanic Formation (CPV) basalts produced during large-scale Lower Carboniferous volcanism (Forsyth *et al.* 1996; Hall *et al.* 1998). Most of the elevated terrain north and south

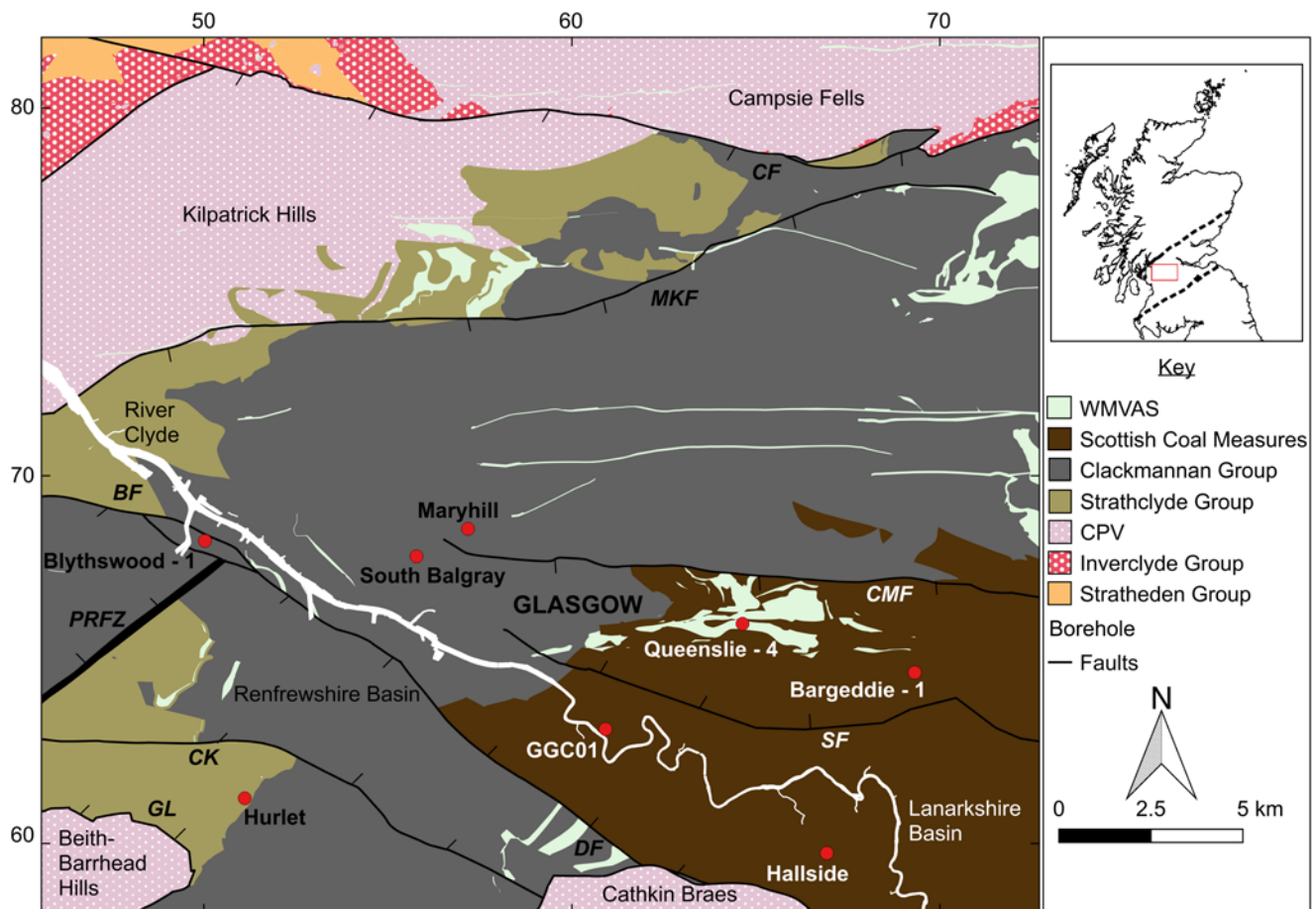


Fig. 1. Simplified solid geology, structure and locations of studied boreholes in Glasgow and the surrounding conurbation, with inset showing location within the Midland Valley of Scotland. Abbreviated stratigraphic units depicted here include: CPV, Clyde Plateau Volcanic Formation of the Strathclyde Group; and WMVAS, Western Midland Valley Westphalian to Early Permian Sills, further information being shown in Table 1. Normal faults, with hanging-wall ticks, are denoted thus: BF, Blythswood Fault; CF, Campsie Fault; CK, Crookston Fault; CMF, Comedie Fault; DF, Dechmont Fault; GL, Glenniffer Fault; MKF, Milngavie-Kilsyth Fault; PRFZ, Paisley Ruck Fault Zone; and SF, Shettleston Fault. The coordinates (north and east) are in kilometres within British National Grid 100 km quadrangle NS.

of the city is formed by these erosion-resistant basaltic lava flows, which occur in largely fault-bounded blocks within the sedimentary sequence.

Stratigraphically below the lavas, the oldest lithologies in the study area range in age from Devonian to Lower Carboniferous and crop out to the NW of the Kilpatrick Hills and Campsie Fells (Fig. 1). They consist of the Stockiemuir Sandstone of the Stratheden Group, a lateral equivalent of the Knox Pulpit Formation in Fife, and the Kinnesswood, Ballagan and Clyde Sandstone formations of the Inverclyde Group (Forsyth *et al.* 1996; Hall *et al.* 1998). Intrusive igneous rocks of latest Carboniferous and/or Early Permian age also crop out, mostly as doleritic sills and dykes (Hall *et al.* 1998; Browne *et al.* 1999).

Boreholes and geothermal measurements

An understanding of the regional heat flow pattern is fundamental to any assessment of geothermal resource potential. Shallow temperature data alone are of little value for the prediction of temperatures at greater depth because the temperature gradient at any site is a function of the local heat flow and thermal conductivity (equation 1), both of which can vary with depth. The investigation of the geothermal potential of the MVS by Browne *et al.* (1985, 1987)

discussed heat flow, thermal conductivity and temperature gradient measurements taken from a variety of boreholes.

For the calculation of one-dimensional vertical heat flow, Fourier's Law takes the form:

$$q = -k \frac{dT}{dz} \quad (1)$$

where q is heat flow, T is temperature, k is thermal conductivity and z is depth.

For horizontally layered stratigraphy, perpendicular to heat flow, a representative thermal conductivity can be determined as the harmonic mean, accounting for the percentage of each lithology present, after, for example, Bott *et al.* (1972) and Westaway & Younger (2016).

The average temperature gradient for boreholes in the MVS is reported as $22.5^\circ\text{C km}^{-1}$ (Browne *et al.* 1987). An anomalous region of higher heat flow has been reported in the west of the Midland Valley, including the Greater Glasgow area (Browne *et al.* 1987; Busby *et al.* 2011). This could be due to east-west crustal thinning, a higher radioactive granitic crustal composition, upward flow of groundwater in the area south of Glasgow, residual heat production from former Tertiary igneous activity, or a combination of two or more of these factors (Browne *et al.* 1987; Robins 1990).

Table 1. Generalized stratigraphic column

Formation	Code	Age	Description	Thickness (m)	
				Glasgow	Airdrie
<i>Scottish Coal Measures Group (CMSC; Carboniferous; Westphalian)</i>					
Upper Coal Measures Fm	UCMS	Bolsovian–Westphalian D	Sst, Slst, Mdst, Strk and C, mostly reddened	85–100 ¹	270 ⁵
Middle Coal Measures Fm	MCMS	Duckmantian	Sst, Slst, Mdst, Lst, C and Strk	160 ¹	160–200 ⁵
Lower Coal Measures Fm	LCMS	Langsettian	Sst, Slst, Mdst, Strk and C	100 ²	100–160 ⁵
<i>Clackmannan Group (CKN; Carboniferous; latest Visean and Namurian)</i>					
Passage Fm	PGP	Arnsbergian–Langsettian	Mainly Sst and fireclay	85 ³	75–200 ⁵
Upper Limestone Fm	ULGS	Pendleian–Arnsbergian	Sst, Dlst, Mdst, marine Lst, C and Strk	250–285 ³	120–300 ⁶
Limestone Coal Fm	LSC	Pendleian	Sst, Slst, Mdst, Lst, C and Strk	270–340 ³	300–360 ⁵
Lower Limestone Fm	LLGS	Brigantian–Pendleian	Sst, Slst, Mdst, marine Lst, with thin C	60–180 ³	100–210 ⁵
<i>Strathclyde Group (SYG; Carboniferous; Visean)</i>					
Lawmuir Fm	LWM	Brigantian	Mainly Sst, with Slst, Mdst, Lst, C and Strk	0–330 ³	0–200 ⁵
Kirkwood Fm	KRW	Asbian–Brigantian	Tuffaceous Mdst and tuffs	0–35 ³	0–35 ⁵
Clyde Plateau Volcanic Fm	CPV	Chadian–Asbian	Basalt, with tuffs and volcanoclastic sediments	300–500 ³	400–900 ⁷
<i>Inverclyde Group (INV; Carboniferous; Tournaisian and earliest Visean)</i>					
Clyde Sandstone Fm	CYD	Chadian	White Sst, part pebbly, part concretionary	0–60 ³	0–100 ⁵
Ballagan Fm	BGN	Courceyan–Chadian	Mdst and thin dolomitic Lst (cementstones)	130–245 ⁴	20–170 ⁵
Kinnesswood Fm	KNW	Courceyan	Red and white Sst, and pedogenic Lst (cornstones)	75–250 ³	150 ⁵
<i>Stratheden Group (SAG; Upper Devonian)</i>					
Stockiemuir Sandstone Fm	SCK	Upper Devonian	Red and grey-purple cross-bedded Sst	400 ³	35 ⁵

This table, based on information from Forsyth *et al.* (1996) and Hall *et al.* (1998), lists the modern BGS stratigraphic terminology for the study area, which supersedes earlier versions. The basal part of the Kinnesswood Formation might date from the uppermost Devonian (Frasnian stage). The Lawmuir Formation is the lateral equivalent of the Upper Oil Shale (UOS) in Figure 2.

Sources: ¹Forsyth & Brand (1986), ²Forsyth (1979), ³Hall *et al.* (1998), ⁴Barnhill borehole, IGS (1978), ⁵Forsyth *et al.* (1996), ⁶Forsyth (1982), ⁷Monaghan (2014). C, Coal; Lst, Ironstone; Lst, Limestone; MdSt, Mudstone; Slst, Siltstone; Sst, Sandstone; Strk, Seatrock.

Eight borehole datasets are assessed in this study (Figs 2 and 3; Table 2). The estimated raw heat flow for Glasgow, based on four of these boreholes, is 60 mW m^{−2} (Browne *et al.* 1987; Busby *et al.* 2011). This section summarizes the available data in each of the boreholes included in this study, details the purpose for which they were drilled and clarifies outstanding data inaccuracies. Borehole summaries are presented in chronological order of drilling.

As was discussed by Thomson (1868) and Thomson *et al.* (1868, 1869), prospecting boreholes for mineral extraction, which had not been developed into a mine shaft, were ideally suited for subsurface temperature measurements. This, in addition to temperature measurements made in boreholes drilled for a variety of purposes, has led to a diverse dataset of temperature measurements for the Glasgow area (Fig. 3; Table 2). This includes measurements made in mineral prospecting boreholes, a National Coal Board (NCB) borehole, British Geological Survey (BGS) boreholes for geothermal and geological mapping research, a commercial borehole for hydrocarbon prospecting and, most recently, a UK Geoenergy Observatories (UKGEOS) geothermal research borehole from the Glasgow Geothermal Energy Research Field Site (GGERFS).

The Blythswood-1 borehole was drilled in 1863 for prospecting for coal and ironstone on the estate of Archibald Campbell, first Baron of Blythswood (Figs 4 and 5). Temperature measurements were made by Lord Kelvin between December 1867 and January 1868 (Thomson *et al.* 1868, 1869). This dataset and that for South Balgray were later assessed by workers determining terrestrial heat flow (Benfield 1939; Anderson 1940).

The South Balgray borehole was drilled in 1864 and temperature measurements conducted by Lord Kelvin in 1869 (Thomson *et al.* 1869). This borehole was drilled to prospect for

coal and ironstone in the Balgray–Gartnavel area (Figs 6 and 7). Previously published reports (Burley *et al.* 1984; Monaghan *et al.* 2017; Busby 2019) have stated the location of the South Balgray borehole as NS 50 75, placing it within the Kilpatrick Hills. According to historical maps (Ordnance Survey 1864), South Balgray farm existed in the present-day location of Hyndland, western Glasgow. The No. 3 Gartnavel borehole is located at the site of South Balgray farm at NS 55780 67810 (BGS Reference NS56NE369). The depth and stratigraphy of the No. 3 Gartnavel borehole is consistent with that reported by Thomson *et al.* (1868, 1869) for the South Balgray borehole. It can be reasonably assumed that the No. 3 Gartnavel borehole is that referred to as South Balgray by Thomson *et al.* (1868, 1869) and all subsequent publications.

The Queenslie-4 borehole was drilled in 1952–53 as one of a series of NCB boreholes in the NE of the city (Fig. 8). Three of the boreholes were cored throughout (Nos 1, 2, and 6) and have since provided valuable sections through the Lower Coal Measures (Forsyth 1979). The Queenslie-4 borehole is ‘open hole’ to a depth of 441 m, meaning that this section of the borehole was not cored.

The Hallside borehole was drilled in 1976 to investigate the Carboniferous stratigraphy in this locality during a resurvey of the North Lowlands District (IGS 1978; Forsyth & Brand 1986). The borehole was logged, and temperature was measured 60 h post-circulation of drilling mud in the borehole (Burley *et al.* 1984). The measured temperature data from the log were digitized in this present study (Fig. 3).

The Hurler House borehole (hereafter Hurler borehole), located on the lands of the former West Hurler House in SW Glasgow (Fig. 9), was drilled as part of research on the Lower Carboniferous of the MVS (IGS 1980). In 1979, the Oxford University Heat Flow Group conducted measurements of thermal conductivity, temperature gradient and heat flow

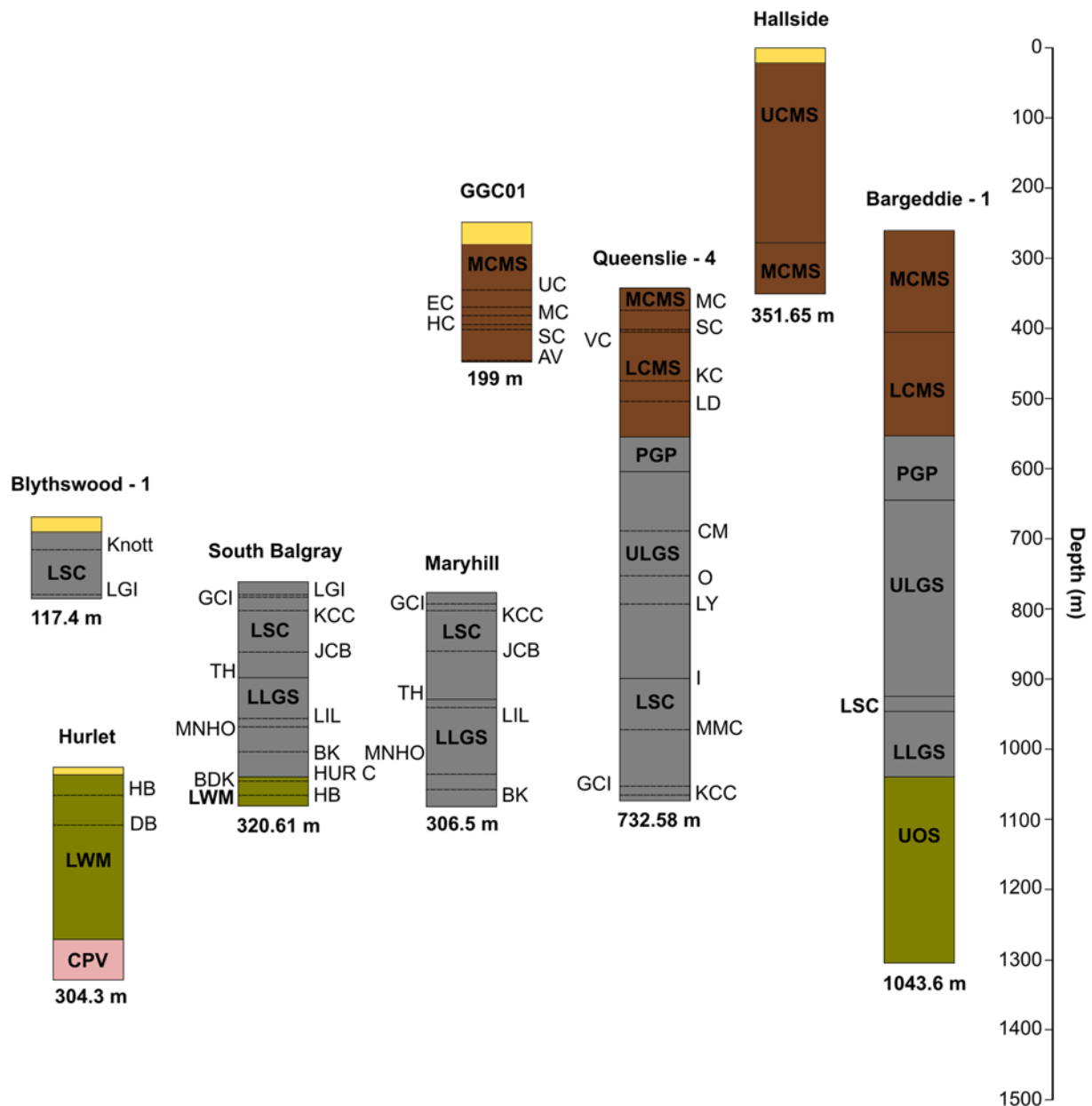


Fig. 2. Borehole stratigraphy for each borehole in Table 2. Arranged west to east (left to right) across study area and correlated stratigraphically. BGS lexicon codes for each formation are given in Table 1. Abbreviations of noted coal and ironstone seams and limestone bands: AV, Airdrie Virtuewell Coal; BDk, Baldernock Limestone; BK, Blackhall Limestone; CM, Calmy Limestone; DB, Dykebar Limestone; EC, Ell Coal; GCI, Garibaldi Clayband Ironstone; HB, Hollybush Limestone; HC, Humph Coal; HUR C, Hurlet Coal; I, Index Limestone; JCB, Johnstone Clayband Ironstone; KC, Kiltongue Coal; KCC, Kilsyth Coking Coal; Knott, Knott Coal; LD, Lower Drumgray Coal; LGI, Lower Garscadden Ironstone; LIL, Lillie's Shale Coal; LY, Lyoncross Limestone; MC, Main Coal; MMC, Meiklehill Main Coal; MNHO, Main Hosie Limestone; O, Orchard Limestone; SC, Splint Coal; TH, Top Hosie Limestone; UC, Upper Coal and VC, Virgin Coal. Queenslie-4 shows the stratigraphy of the first 441 m of the borehole, which was 'open hole' and not cored. Yellow ornament denotes Quaternary deposits. Data from IGS (1977, 1978, 1980), *Monro (1983)*, *Barron & Burkin (2019)*, BGS online borehole viewer, BGS graphic borehole logs, UKOGL online interactive map.

(*Oxburgh 1982; Burley et al. 1984*). These data, unpublished at the time, were kindly provided for this study by Jon Busby of BGS and have since been published (*Busby 2019*). The upper 250 m of the Hurlet borehole consists of thin beds of sandstone, siltstone, mudstone, seatearth and coal. *Oxburgh (1982)* made measurements of temperature gradient and thermal conductivity over 5 m intervals. Thermal conductivity was measured using the divided bar method; however, a number of samples obtained between 0 and 95 m depth disintegrated, limiting those available for analysis. The rapid variation of lithology meant that the value of thermal conductivity measured for any one interval was not

necessarily representative of rocks within that interval. *Oxburgh (1982)* therefore only reported values of temperature gradient and thermal conductivity from intervals in the depth range of 95–295 m, as these consisted of rocks for which thermal conductivities were known (Table 3). Based upon these values of thermal conductivity and temperature gradient, using equation (1), *Oxburgh (1982)* calculated the heat flow at each interval and the average heat flow across 95–295 m as 60 mW m^{-2} . Temperature measurements were not included in the *Oxburgh (1982)* dataset; however, they have been calculated for the present study (Fig. 3) using the following procedure. The annual mean surface air

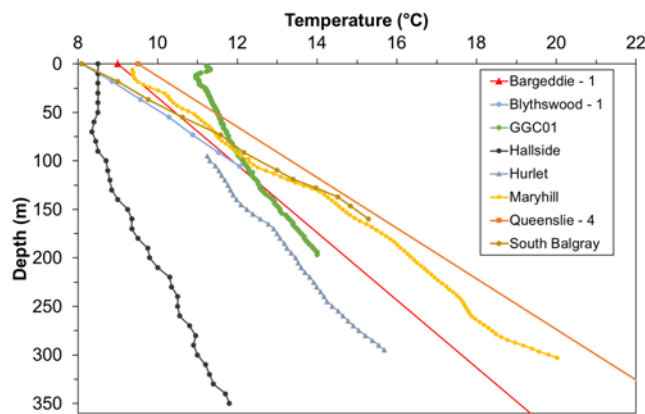


Fig. 3. Borehole temperature measurements for the eight boreholes included in this study. Depth axis limited at 350 m to show datasets (Blythswood-1, GGC01, Hallside, Hurllet, Maryhill, and South Balgray) with greater resolution. Bargeddie-1 and Queenslie-4 extend to respective bottom-hole temperatures shown in Table 2. Data summarized in Table 2.

temperature for the Hurllet borehole is calculated as 9.15°C from the monthly maximum and minimum temperature observations from 1979 at the Paisley weather station (Met Office 2019). We calculated a harmonic mean thermal conductivity of $2.86\text{ W m}^{-1}\text{ }^{\circ}\text{C}^{-1}$ by applying values of thermal conductivity (Table 3) to each lithology present in the borehole log across the 95–295 m depth range. With a harmonic mean thermal conductivity of $2.86\text{ W m}^{-1}\text{ }^{\circ}\text{C}^{-1}$ and heat flow of 60 mW m^{-2} , equation (1) gives a temperature gradient of $c. 21^{\circ}\text{C km}^{-1}$. Using this temperature gradient and the 9.15°C surface temperature, a temperature of 11.15°C is estimated at a depth of 95 m. Finally, using this starting value, temperature values were reconstructed across 95–295 m depth based upon the values of temperature gradient for each 5 m interval from Oxburgh (1982).

The Maryhill borehole was drilled by BGS in 1983 as a first step towards assessing the geothermal resource base within Glasgow (Wheildon *et al.* 1985). This borehole was sited to give a 300 m sequence of rock, free of old mine workings, with a minimum thickness of porous sandstones, the objective being to obtain accurate measurements of the temperature gradient, undisturbed by moving groundwater (Monro 1983). Temperature was measured at 99 depths between 100 and 303 m depth (Fig. 3), together with 82 thermal conductivity measurements on core (Browne *et al.* 1987). Burley *et al.* (1984) and subsequent publications (e.g. Monaghan *et al.* 2017) recorded the ground surface elevation of the site of this borehole as 55 m above sea-level. From a site visit to the location it has been ascertained that the ground surface is 40 m above sea-level. The borehole is located on a former railway siding, connecting a branch of the Lanarkshire and Dunbartonshire railway from Maryhill Central station to the former Maryhill Ironworks (Ordnance Survey 1914a). Construction of the railway siding and adjacent, deeper, railway cutting (now infilled) altered the terrain at the site.

The Bargeddie-1 borehole was drilled in 1989 to test for hydrocarbons in the Houston Sandstone in the Upper Oil Shale Group, a lateral equivalent of the Lawmuir Formation (Fig. 2; Table 1).

Table 2. Borehole data

Name	NGR	BGS ref	Date*	Height† (m)	Z‡ (m)	Z1§ (m)	Z2§ (m)	T (°C)	Q (mW m ⁻²)	Type	Ref¶
Blythswood-1	NS 50030 68230	NS56NW58	1868.01	2	117.4	18	105	12	52	EQM	A, B, C
South Balgray	NS 55780 67810	NS56NE369	1869.07.13	30	320.61	0	137	15.3	64	EQM	A, B, C
Queenslie-4	NS 64640 65975	NS66NW326	1952	77.6	732.58	0	691	36	—	BHT	A, C
Hallside	NS 66930 59740	NS65NE66	1976.04.26	54.22	351.65	0	350	11.8	—	LOG	C, D
Hurllet	NS 51110 61230	NS56SW333	1979.5.18	30.31	304.3	95	295	—	60	—	C, D
Maryhill	NS 57178 68558	NS56NE1755	1983.12.18	40	306.5	100	303	20.03	63	EQM	C, D
Bargeddie-1	NS 69318 64649	NS66SE415	1989.08.13	78	1043.6	0	1043.6	39	—	DST	D, E
GGC01	NS 60915 63109	NS66SW3754	2018.12.12	9.66	199	0	196.8	14	—	LOG	F

*Date corresponds to date of last temperature measurement. If not stated, then taken as the same as the date that drilling concluded.

†Height (m) above sea-level taken from borehole log.

‡Z is depth of well bottom taken from borehole log.

§Z1 to Z2 is the depth range over which heat flow Q is measured. For boreholes where Q is not measured, Z2 also corresponds to depth of deepest temperature measurement.

||Type of measurement: BHT, bottom-hole temperature measurement; DST, drill stem test; EQM, equilibrium measurement; LOG, log temperature.

¶References: A, BGS borehole log; B, Thomson *et al.* (1869); C, Burley *et al.* (1984); D, previously unpublished data provided from BGS within the BritGeothermal research partnership, now published in Busby (2019); E, UK Onshore Geophysical Library, F, Starcher *et al.* (2019).

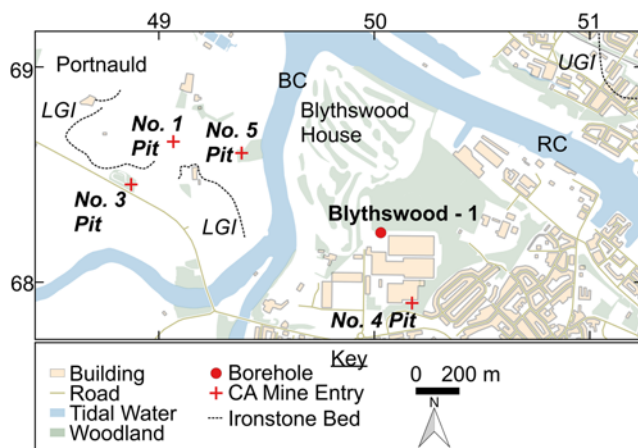


Fig. 4. Map of present-day land use of the former Blythwood Estate in the vicinity of the Blythwood-1 borehole, showing locations discussed in the text. LGI and UGI denote the Lower and Upper Garscadden Blackband Ironstone beds, respectively; BC, Black Cart Water; RC, River Clyde; CA mine entry, Coal Authority mine entry. The coordinates are in kilometres within British National Grid 100 km quadrangle NS.

The GGC01 borehole was drilled between 19 November and 12 December 2018 as one of 12 boreholes at the UKGEOS GGERFS in the Clyde Gateway Redevelopment area in Dalmarnock, in the east end of Glasgow. The borehole was wireline logged in December 2018, providing temperature measurements to a depth of 196.8 m (Starcher *et al.* 2019). This temperature record has been digitized for the present study (Fig. 3).

Legacy of mineral extraction

Scottish coal production, almost entirely in the Central Belt of Scotland, peaked in 1913 at $c. 44 \times 10^6 \text{ t a}^{-1}$ (Younger 2001). When the coal industry was nationalized in 1947, there were 225 collieries in Scotland; now there are none. The last pits to close were Monktonhall (1998) near Edinburgh and Longannet (2002) in Fife (Northern Mine Research Society 2018). The Limestone Coal Formation was the

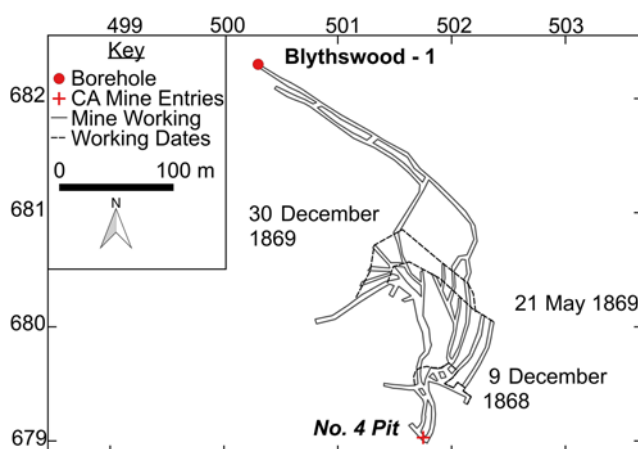


Fig. 5. Blythwood No. 4 Pit, workings and location of Blythwood-1 borehole (Blythwood Estate 1871), [TD 234/54/3]. Workings digitized from Item TD 234/54/3 of the Glasgow Archives at the Mitchell Library, Glasgow. The coordinates (north and east) are in 100 m intervals within British National Grid 100 km quadrangle NS. CA mine entries, Coal Authority mine entries.

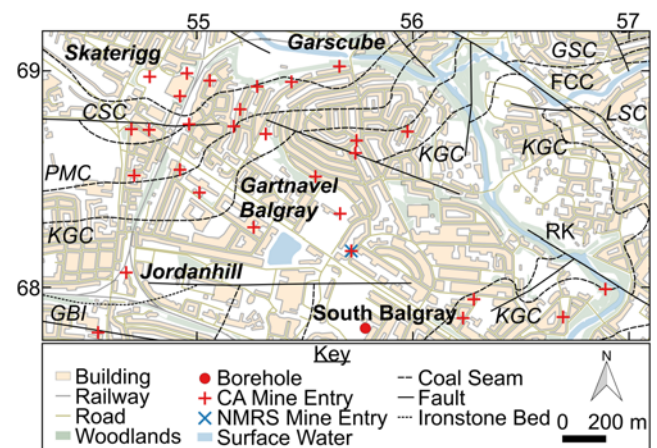


Fig. 6. Map of present-day land use at the locality of the South Balgray borehole. Location of historical mine entries obtained from the Northern Mine Research Society (NMRS), Coal Authority (CA) and National Records of Scotland (1872) are shown. Mineral fields mentioned in text are annotated. CSC, Cowglen Slutty Coal; FCC, Forth and Clyde Canal; GBI, Garscadden Blackband Ironstone; GSC, Glasgow Shale Coal; KGC, Knightswood Gas Coal; LSC, Limestone Coal Formation; PMC, Possil Main Coal and RK, River Kelvin. The coordinates are in kilometres within British National Grid 100 km quadrangle NS.

principal source of coal in Glasgow, but coal seams in other formations have also been extensively mined, particularly the Middle and Lower Coal Measures and the Upper Limestone Formation (Table 1) (Hall *et al.* 1998). Extensive mining and quarrying of ironstone, alum, shale and building stone also took place. Two historical mining basins encompass the borehole locations in this study: the Lanarkshire and Renfrewshire basins (Fig. 1); these collectively form the Scottish Central Coalfield. Mine shafts and collieries near each borehole location are detailed in Tables 4 and 5.

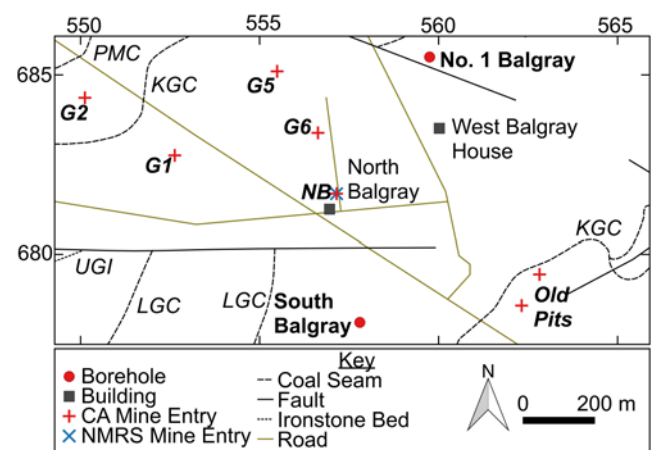


Fig. 7. Summary historical map of South Balgray and surrounding area. Road and building features shown on map obtained from 1:10 560 County Series 1st Edition Ordnance Survey Map. Location of historical mine entries obtained from the Coal Authority (CA) and Northern Mine Research Society (NMRS) are shown. G1, Gartnavel No. 1 Pit; G2, Gartnavel No. 2 Pit; G5, Gartnavel No. 5 Pit; G6, Gartnavel No. 6 Pit; KGC, Knightswood Gas Coal; LGC, Lower Garscadden Coal; NB, North Balgray Old Coal Shaft; PMC, Possil Main Coal; UGI, Upper Garscadden Ironstone. The coordinates (north and east) are in 100 m intervals within British National Grid 100 km quadrangle NS. Historical map data: © Crown Copyright and Landmark Information Group Limited (2019). All rights reserved. (1864, 1865).

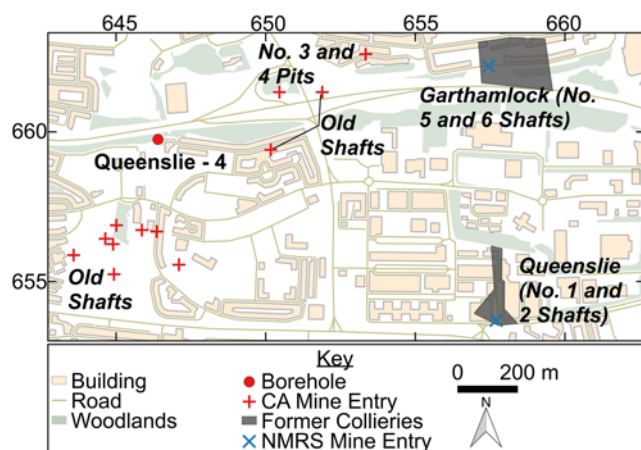


Fig. 8. Map of present-day land use at the locality of the Queenslie-4 borehole. Location of historical mine entries obtained from the Northern Mine Research Society (NMRS) and the Coal Authority (CA) are shown. Location and extent of Queenslie and Garthamlock Collieries obtained from 1:10 560 County Series 3rd Revision Ordnance Survey Map. The coordinates (north and east) are in 500 m intervals within British National Grid 100 km quadrangle NS. Historical map data: © Crown Copyright and Landmark Information Group Limited (2019). All rights reserved. (1935, 1937, 1946, 1947).

In the early twentieth century, the Lanarkshire Basin was the most important mining area in Scotland and one of the most significant in the UK, with a full thickness of the Coal Measures containing valuable seams of coal and Blackband Ironstone (Scottish Mining Website 2018). Situated south and east of Glasgow, and including much of the city itself, the Lanarkshire Basin (Fig. 1) was host to major technological advances in coal mining. The huge market for coal and ironstone in the Glasgow conurbation, in particular from the iron and steel industry, was pivotal in the development of the mining industry (Oglethorpe 2006). The South Balgray, Queenslie-4, Hallside, Maryhill and Bargeddie-1 boreholes lie within this region (Fig. 1).

The Blythwood-1 and Hurlet boreholes lie SW of Glasgow in Renfrewshire (Fig. 1). Skillen (1990) provides

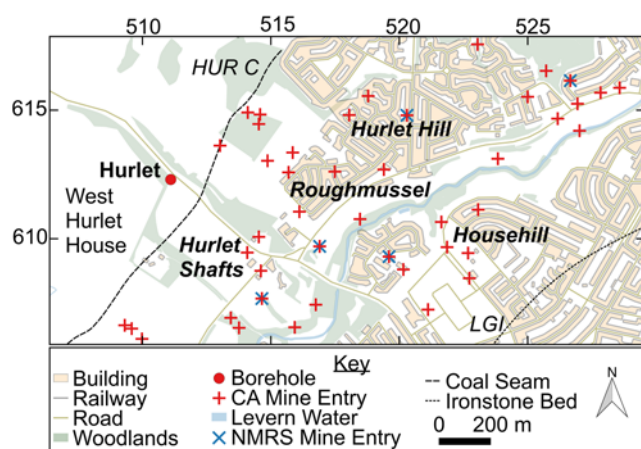


Fig. 9. Map of present-day land use at the locality of the Hurlet borehole. Location of historical mine entries obtained from the Northern Mine Research Society (NMRS) and the Coal Authority (CA) are shown. HUR C, Hurlet Coal; and LGI, Lower Garscadden Blackband Ironstone. The coordinates (north and east) are in 500 m intervals within British National Grid 100 km quadrangle NS.

a thorough overview of mineral exploration and the industrial development of Renfrewshire. One of the only coal seams of economic value in the Lower Limestone Group is the Hurlet Coal (MacGregor *et al.* 1920). The exploitation of coal in this locality was longstanding. A lease dated 1634 said that five miners were employed at Hurlet Colliery (Skillen 1990) and in 1812 it was stated that coal had been wrought here for at least 300 years (Smart 1996). As well as being rich in coal, the Hurlet Coal seam contained minerals that were used to produce iron (II) sulfate and alum, used in the dyeing process by the numerous cotton printing works in the Hurlet area (Skillen 1989; Smart 1996). In addition, the Hurlet area was extensively worked for limestone, it being the type locality for the Hurlet Limestone.

Robins (1990) suggested that Glasgow is the focal point for much of the groundwater discharge from the Central Coalfield, with prevailing groundwater flow paths from the east, NE and SE. However, the hydrogeology of Glasgow and the Lanarkshire Coalfield is not well understood (Ó Dochartaigh *et al.* 2018). If it behaves like the better-studied hydrogeological systems of NE England (e.g. Younger 1993, 1995; Younger & Harbourn 1995; Younger *et al.* 2015; Westaway & Younger 2016), horizontal components of heat flow can be expected, carried by groundwater flow, from the workings in the vicinity of the aforementioned boreholes to increase temperatures in the mines below other areas of Glasgow. Despite the extensive mining heritage of Glasgow and the surrounding conurbation, limited information is currently available on the connectivity of the mine workings or the hydraulic properties of the coal- and ironstone-bearing strata in the MVS (Ó Dochartaigh *et al.* 2018).

Chronology of mining

This section details the timing, duration and proximity of mineral prospecting and extraction at each of the borehole locations to investigate the influence of the presence of mine workings on existing borehole temperature and heat flow measurements in Glasgow.

Blythwood-1

Blackband Ironstone and Clayband Ironstone were extensively mined on the Blythwood Estate in the mid- to late nineteenth century. Shown in Figure 4, east of the Black Cart Water, it was mined over a small area from the chief pit, No. 4 Pit Blythwood. This pit, 148 m deep, was situated in the grounds of Blythwood House (Hinxman *et al.* 1920; MacGregor *et al.* 1920), in close proximity to the Blythwood-1 bore (Fig. 4).

Based upon Item TD234/54/3 of the Glasgow Archive, Figure 5 illustrates the timing and extent of mining on the Blythwood Estate east of the Black Cart Water. The No. 4 Pit and related workings are dated 9 December 1868, 21 May 1869 and 30 December 1869. The Blythwood-1 bore is also noted on the plan, with workings dated from 30 December 1869 extending to this location. Table 5 shows that the Blythwood mine was abandoned on 26 April 1875 (Home Department 1889; Mines Department 1931).

From this information the chronology of mining on the Blythwood Estate can be established. From the early to mid-1860s exploratory boreholes, such as the Blythwood-1 bore,

Table 3. *Hurlet thermal conductivity values*

	Mdst	Sst	Slst	Coal	Lst	Ist	Strk	Basalt	Volc. det
k (W m ⁻¹ °C ⁻¹)	1.40*	4.71 [†]	3.02 [‡]	0.4 [§]	2.85 [§]	2.85 [§]	2.42 [†]	2 [†]	2.35 [†]

*Bullard & Niblett (1951); [†]Oxburgh (1982); [‡]Herrin & Deming (1996); [§]England *et al.* (1980). Mdst, Mudstone; Sst, Sandstone; Slst, Siltstone; Lst, Limestone; Ist, Ironstone; Strk, Seatrock; Volc. det, Volcanic detritus.

were sunk to prospect for Blackband and Clayband Ironstone. Lord Kelvin conducted subsurface temperature observations at Blythwood-1 bore from December 1867 to January 1868 (Thomson *et al.* 1869). From December 1868 to December 1869, workings were developed from No. 4 Pit, extending close to the Blythwood-1 bore. On 26 April 1875 the Blythwood ironstone workings were abandoned. Based upon this, the measurements made by Lord Kelvin would not have been influenced by the effect of mine workings close to the Blythwood-1 borehole and are therefore a good approximation for the undisturbed thermal state.

South Balgray

As already noted, the South Balgray borehole is located to the south of the Gartnavel–Balgray mineral field. There are numerous pits within the Gartnavel–Balgray field sunk to Gas Coal, Blackband Ironstone and Clayband Ironstone (Fig. 6; Table 5). Extensive mining north of the South Balgray borehole took place prior to the date on which temperature measurements were made by Lord Kelvin (Table 5; Fig. 7). At various pits at Gartnavel, coal and ironstone were worked until abandonment in 1874. Of particular relevance is the entry for Gartnavel No. 5 and No. 6, which states that Garibaldi and Blackband Ironstone were worked in 1869. The entry for Balgray states that Blackband Ironstone was worked in 1866. For Balgray and Gartnavel Pits, seams of coal and ironstone were worked until abandonment in 1880.

The location of mine shafts in the Gartnavel–Balgray field are shown in Figure 7. The workings closest to the South Balgray borehole at North Balgray Farm are Clayband Ironstone workings (Addie *n.d.*). Garibaldi Clayband, or Upper and Lower Garscadden Blackband Ironstone are the most likely seams to have been worked here (Hinxman *et al.* 1920). The workings extending from Gartnavel No. 6 are dated 25 July 1865 and 14 December 1869. The earliest workings in this area between Balgray Farm and West Balgray House are Gas Coal workings dated 22 March 1864. The Blackband Ironstone workings are dated 1866.

From Figure 2, the South Balgray borehole encountered the Lower Garscadden Ironstone at a depth of *c.* 18 m and the Garibaldi Clayband Ironstone at a depth of *c.* 22 m. The Upper Garscadden Ironstone and California Ironstone were

not encountered in the South Balgray borehole, lying stratigraphically above the surface geology at the site.

The temperature observations in the South Balgray borehole were recorded by Lord Kelvin at the same time as mining activity took place in the Gartnavel–Balgray mineral field. However, based upon the plan of workings in the Gartnavel–Balgray field, the South Balgray borehole lies outside the extent of the workings. Furthermore, those seams worked in the Gartnavel–Balgray field lie at relatively shallow depth within the South Balgray borehole. It may therefore be reasonably concluded that the temperature measurements were not influenced by mining and are a good approximation for the undisturbed thermal state.

Queenslie-4

Extensive coal mining activity took place at Queenslie and the surrounding areas of Shettleston and Garthamlock in the East End of Glasgow through the nineteenth century and into the early twentieth century. Illustrated in Figure 8, the two prominent collieries and associated mine shafts in the area of the Queenslie-4 borehole are Queenslie Colliery and Garthamlock Colliery. Detailed in Table 4, both collieries ceased operation in 1935, around two decades prior to the drilling of the Queenslie-4 borehole. This was drilled to a depth of 732.58 m and the temperature was measured at 691 m below ground level (Table 2). The first 441 m of the borehole was not cored and is described in the borehole log as ‘open hole’. This section of the borehole contains coal seams mined in the locality. Table 5 shows that at Queenslie Colliery, Virgin and Virtuewell Coal were worked. The Queenslie-4 borehole encounters the Virgin Coal seam at a depth of *c.* 64 m and, while there is no note within the log of the Virtuewell seam, this would lie between 64 m and the Kiltongue Coal at *c.* 134 m depth (Fig. 2). This borehole is located on the site of former Cranhill Quarry [NS 64900 65930] and in close proximity to Cranhill Fireclay works [NS 65060 65920]. The associated industrial processes at these works may have caused additional warming of the shallow subsurface. This shall be studied in future work.

The Queenslie-4 borehole is located in an area of Glasgow with an extensive history of mining which took place prior to the date at which the borehole was drilled, and the

Table 4. *Mine entries near borehole locations*

Mine name	BNG ref	Mineral worked	Open	Abandonment
Bargeddie	NS 69975 64265	Coal	1854	1920
Hallside	NS 66935 59675	Coal	1873	1921
Queenslie	NS 65770 65370	Coal, Fireclay	1908	1935
Garthamlock	NS 65745 66220	Coal	1854	1935
Balgray	NS 55715 68168	Coal	1873	1880

Summarized from Northern Mine Research Society (2018) where data is available.

Table 5. Mine entries near borehole locations

Name	Mineral worked	Seam name and working date	Abandonment date
Bargeddie	Coal	UC, MC, PC, SC (1860, 62), VC, KC (1870, 97)	14 October 1921
Blythswood	Ironstone	BI, CI	26 April 1875
Hallside	Coal	UC, EC, PC, MC, SC, VC	31 December 1921
Hurlet	Coal	HUR C (1840)	—
Hurlet	Ironstone	Worked 1849 and 1854	—
Hurlet	Limestone	Worked 1865	—
Ruchill No. 4, 6	Ironstone	CCI (1864), GCI (1872)	—
Queenslie	Coal	VC	28 May 1929
Queenslie No. 1, 2	Coal	VWC	28 July 1911
Balgray	Ironstone	BI (1866)	—
Balgray; Gartnavel Nos 1, 3–10	Coal	DC, MC, GC	Prior to 1880
Balgray; Gartnavel Nos 1, 3–10	Ironstone	BI, CI	Prior to 1880
Gartnavel, No. 1	Ironstone	Worked 1872	—
Gartnavel, No. 9	Coal	WC	18 September 1874
Gartnavel, Nos 1, 2	Ironstone	BI, GCI (1873)	—
Gartnavel, Nos 1, 3, 4, 5, 6, 8	Coal	GC, MC (1873)	—
Gartnavel, Nos 1, 3, 4, 5, 6, 8	Ironstone	BI, GCI (1869)	—
Dalmarnock	Coal	UC, EC (1833–56), MC (1849), HC, SC (1858)	—
Govan No. 5	Coal	UC, EC, MC, HC, SC, VWC, KC	1923.06.23

Summarized from [Mines Department \(1931\)](#). Abbreviations of noted coal and ironstone seams and limestone bands: BI, Blackband Ironstone; CCI, Californian Clayband Ironstone; CI, Clayband Ironstone; DC: Davie Coal; EC, Ell Coal; GC, Gas Coal; GCI, Garibaldi Clayband Ironstone; HUR C, Hurlet Coal; KC, Kiltongue Coal; MC, Main Coal; PC, Pyotshaw Coal; SC, Splint Coal; UC, Upper Coal; VC, Virgin Coal; VWC, Virtuewell Coal; WC, Wee Coal.

temperature measured. While the extent of the mine workings associated with the pits at Garthamlock and Queenslie is unknown, examination of historical maps places the borehole some distance from former shafts. The seams of coal worked in this area lay between *c.* 64 and *c.* 134 m in the Queenslie-4 borehole. Given that only one temperature measurement was recorded in the borehole at 691 m depth, no conclusion can be drawn as to whether the temperature gradient in the top *c.* 134 m of the borehole is perturbed by mine workings. However, the temperature measurement at 691 m can be considered a good approximation for the undisturbed thermal state at this depth.

Hallside

Hallside Village was originally built to serve the nearby Hallside Colliery and expanded when the Hallside Steelworks opened in 1872 ([Hall 2012](#)). The Hallside Steelworks was one of the major steel-producing centres in Scotland until its closure in 1979 ([Shepherd 1996](#)). Hallside Colliery opened in 1873 and closed in 1921 ([Mines Department 1931](#)). The Hallside borehole is located on the site of the former Hallside Colliery ([Fig. 10](#)). From [Table 5](#), pits at Hallside Colliery worked seams of Upper Coal, Ell Coal, Pyotshaw Coal, Main Coal, Splint Coal and Virgin Coal.

After closure of the Hallside Colliery, neighbouring collieries continued to work coal seams beneath the area of Hallside until closure in the 1960's. Those pits which remained active at this time were Blantyreferme 1, 2, and 3 ([National Coal Board 1961a](#)). It is stated that these pits were working the Virtuewell, Lower Drumgray and Blackband seams ([National Coal Board 1961b](#)). Blantyreferme 1 & 2 closed in 1962 and Blantyreferme 3 in 1964 ([Oglethorpe 2006](#)).

[National Coal Board \(1961b\)](#), shows the extent and timescale in which each seam of coal was worked at the

Hallside and Blantyreferme pits. The plans show Main Coal workings dated January 1890 and January 1892, Virgin Coal workings dated 04 October 1910, Pyotshaw Coal workings dated 18 January 1915, Humph Coal workings dated April 1920, Upper Coal workings dated 17 June 1932 and Ell Coal workings dated 21 March 1944. The depths of the worked seams are shown in [Figure 11](#). All but a few of the plans show worked seams that are either in close proximity to or lie directly beneath the location of the Hallside borehole.

In the Hallside borehole, the base of the Upper Coal Measures was encountered at *c.* 279 m depth, with the borehole terminating at a depth of *c.* 352 m ([Figs 2 and 11](#)). Another borehole, named the 'Hallside Colliery' borehole, was sunk from within the mine workings at *c.* 265 m depth to a depth of *c.* 451 m to give a section of the stratigraphy at the colliery. It is assumed that the depth of each seam is the same in the 'Hallside Colliery' borehole as in the Hallside borehole ([Fig. 11](#)). [Clough *et al.* \(1920\)](#) state that at Hallside Colliery, the Middle Coal Measures were overlain by around 293 m of Upper Coal Measures. This aligns relatively well with the boundary of the Upper Coal and Middle Coal Measures observed in the Hallside borehole ([Fig. 11](#)), indicating that there is indeed close alignment between the depths of seams in the Hallside borehole and those worked in the Hallside Colliery.

Given the proximity of the Hallside borehole to steelworks ([Ordinance Survey 1914b](#)), related industrial processes may have an influence on the downward propagation of heat conduction from the surface to the shallow subsurface (cf. [Westaway & Younger 2016](#)). Assessment of this effect is beyond the scope of the current study, but it will be explored in future work.

In summary, the Hallside borehole is located on the site of the former Hallside Colliery and within the extent of mine workings associated with the steelworks. Extensive mining activity had taken place at this site prior to the drilling of the borehole and the measurement of temperature therein. The

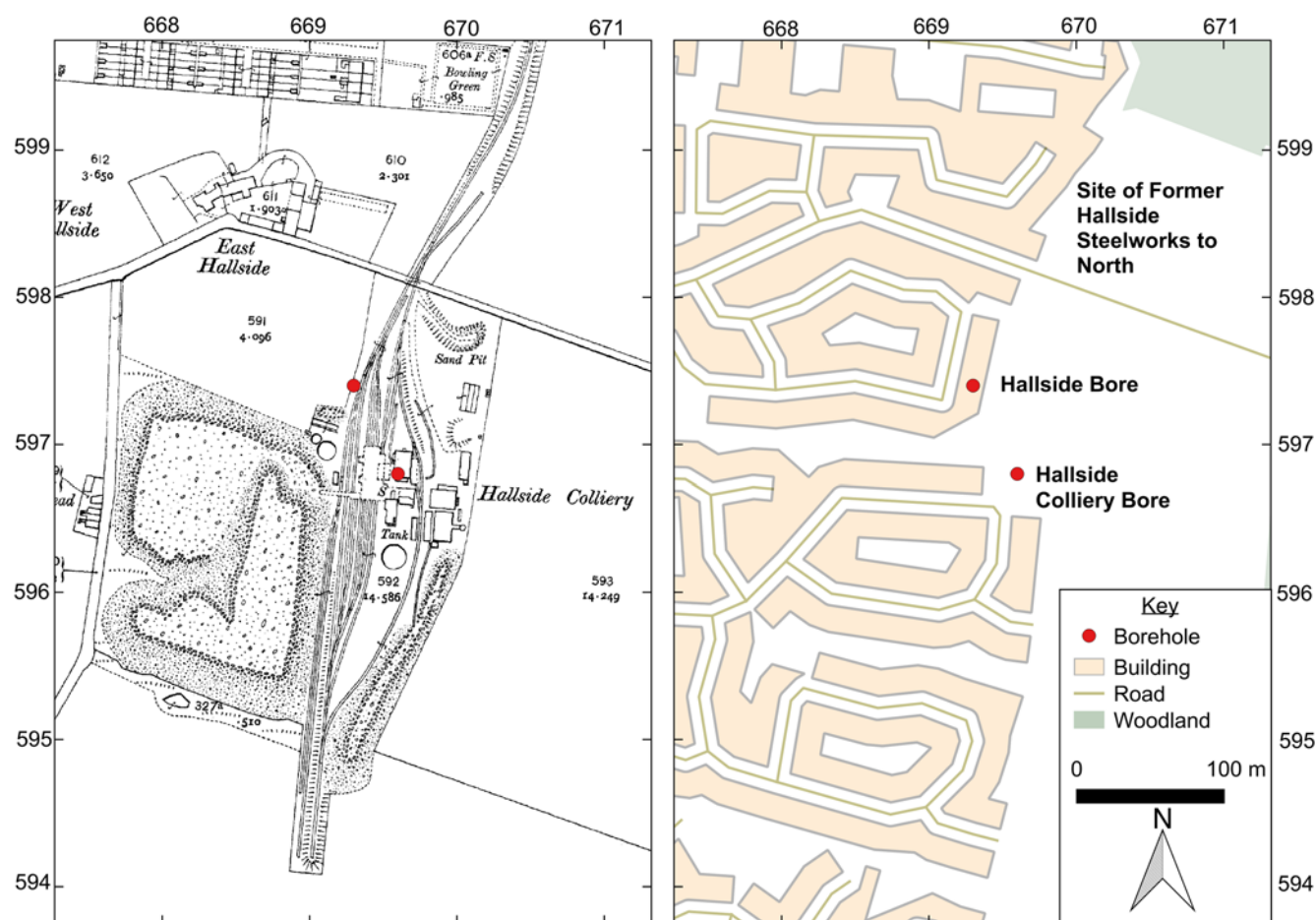


Fig. 10. Historical map and present-day land-use map at the locality of the Hallside BGS borehole, showing proximity of the former Hallside Colliery (closed in 1921). The coordinates are in 100 m intervals within British National Grid 100 km quadrangle NS. Historical data: © Crown Copyright and Landmark Information Group Limited (2019). All rights reserved. (1914).

seams worked were deeper than the base of the borehole and of the deepest temperature measurement. This evidence suggests that there may be a potential influence from this legacy of mining on the flow of heat in the subsurface and is perhaps a contributing factor as to why a low bottom-hole temperature, and associated heat flow, was observed in the Hallside borehole.

Hurlet

By the 1830s limestone was mined at Hurlet from pits up to 70 m deep (Dron 1902; Nisbet 2006). Hinxman *et al.* (1920) state that Hurlet Limestone can be seen at the mouth of an old mine south of West Hurlet House. The Hurlet Coal seam extended over *c.* 500 acres of land and was worked from various pits either side of the village (Fig. 9) (Hinxman *et al.* 1920).

The extent of the mining activity is shown on Figure 9, with numerous pits dotted throughout the area SW of the outcrop of the Hurlet Coal seam. The lands of West Hurlet House, and the location of the Hurlet borehole, lie NE of the outcrop of the Hurlet Coal, and outside the area in which the coal was wrought. As shown in Figure 2, the Hurlet borehole is drilled through a sequence of the Lawmuir Formation, stratigraphically below the Hurlet Coal seam and other worked minerals in the Lower Limestone Group.

It is therefore unlikely that coal, ironstone or limestone were worked at significant depths in the vicinity of the Hurlet borehole on the grounds of West Hurlet House. However, surface and/or shallow mining for Hurlet Coal or Hurlet Limestone may have taken place close to the location of the Hurlet borehole. Data available from Oxburgh (1982) are limited to a depth range of 95–295 m and the influence of potential surface/shallow workings cannot be observed. These data can be considered a good approximation for the undisturbed thermal state across the measured depth range.

Maryhill

As already noted, the Maryhill borehole is located to the east of the Gartnavel–Balgray mineral field, separated by the River Kelvin and the Forth and Clyde Canal (Fig. 12). The Maryhill borehole is situated *c.* 100 m from the site of the former Maryhill Ironworks (Ordnance Survey 1914a). From historical Ordnance Survey maps of the area, the ironworks operated from 1877 until the mid-1900s. As at Hallside, heat produced from the Maryhill Ironworks may have propagated into the shallow subsurface and influenced local heat flow.

Table 5 details mining activity around the area of Maryhill. The Garibaldi and California Clayband ironstones were worked at Ruchill No. 4 and 6 pits, east of the Maryhill borehole (Fig. 12). South of the Maryhill borehole and east of the Balgray–Gartnavel field, the Garibaldi

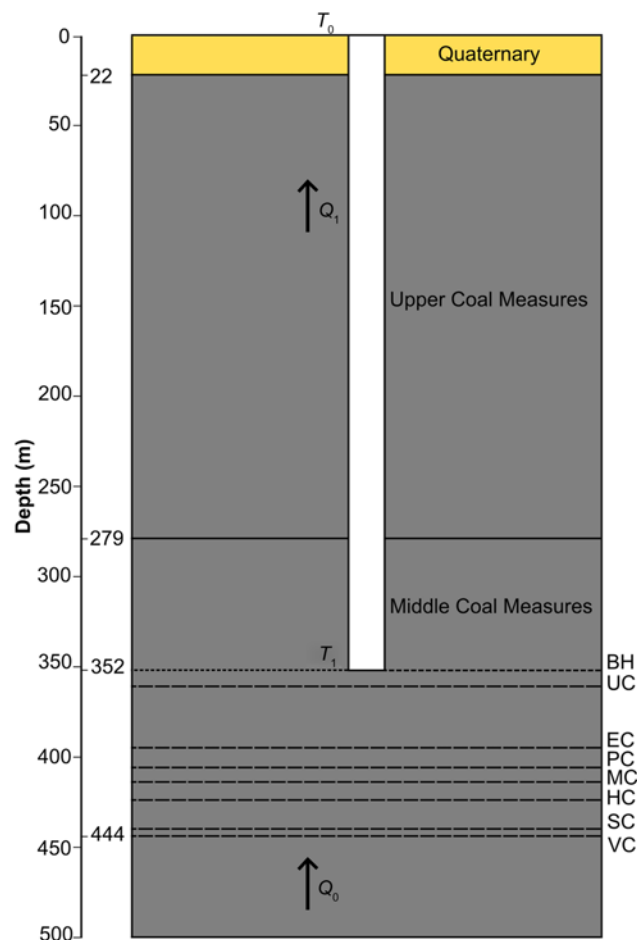


Fig. 11. Schematic log of the Hallside Borehole [NS 66930 59740] showing summary stratigraphy including seams worked at the Hallside Colliery (depths from the log of the Hallside Colliery bore [NS 66960 59680]). BH, Bottom Hole; EC, Ell Coal; HC, Humph Coal; MC, Main Coal; PC, Pyotshaw Coal; SC, Splint Coal; UC, Upper Coal and VC, Virgin Coal. Yellow ornament denotes Quaternary deposits. Q_0 denotes the heat flow below mine workings, Q_1 denotes the heat flow above mine workings, T_1 denotes the deepest temperature measurement in the borehole and T_0 denotes the surface air temperature.

Clayband Ironstone was raised from several pits in the Eastpark district of Maryhill (MacGregor *et al.* 1920). The Garibaldi Clayband Ironstone seam was encountered at a depth of *c.* 16 m in the Maryhill borehole (Fig. 2). The California Ironstone lies above the Garibaldi Clayband Ironstone in the stratigraphy of this area. It would therefore appear that the California Clayband Ironstone seam was not encountered in the Maryhill borehole.

The Kilsyth Coking Coal was encountered at *c.* 26 m depth in the Maryhill borehole (Fig. 2). Hinxman *et al.* (1920) stated that this was the lowest workable seam in the Limestone Coal Formation. The Maryhill borehole is located in an area of Glasgow with a history of mining prior to the drilling of the borehole. While the extent of the mine workings at Eastpark are unknown, the seams of coal worked in this area of Glasgow lay at shallow depth relative to the borehole. From examination of the temperature gradient in the shallow *c.* 30 m of the borehole, it is unclear as to whether shallow mine workings have disturbed the thermal state. Additional factors such as the downward propagation of heat from the Maryhill Ironworks may counteract the dispersion of heat flow locally into mine

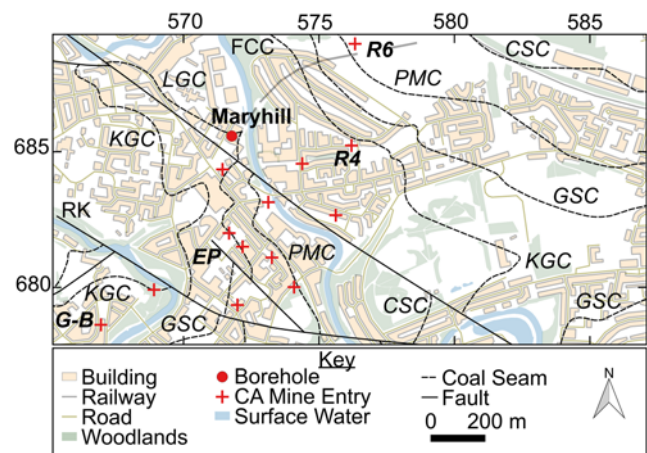


Fig. 12. Map of present-day land use at the locality of the Maryhill borehole. Location of historical mine entries obtained from the Coal Authority (CA) shown. CSC, Cowglen Sluttly Coal; EP, Eastpark; FCC: Forth and Clyde Canal; G-B, Gartnavel-Balgray; GSC, Glasgow Shale Coal; KGC, Knightswood Gas Coal; LGC, Lower Garscadden Clayband Ironstone; LSC, Limestone Coal Formation; PMC, Possil Main Coal; R4, Ruchill No. 4; R6, Ruchill No. 6 and RK, River Kelvin. The coordinates (north and east) are in 500 m intervals within British National Grid 100 km quadrangle NS.

workings. However, the temperature measurements made below 30 m depth appear to be a good approximation for the undisturbed thermal state at this site.

Bargeddie-1

The Bargeddie-1 borehole is drilled in an area known to have been extensively mined for coal throughout the nineteenth century (Table 5). This borehole is located close to a number of mine shafts related to the Bargeddie and Bartonshill collieries (Fig. 13). From the end of well report, a relatively complete section of Middle and Lower Coal Measures was encountered (Teredo Petroleum PLC 2000). Within the Middle and Lower Coal Measures, to a depth of 293 m, four coals are known to have been worked at the site, the Upper, Main, Splint and Kiltongue seams (Teredo Petroleum PLC 2000). This is consistent with Table 5.

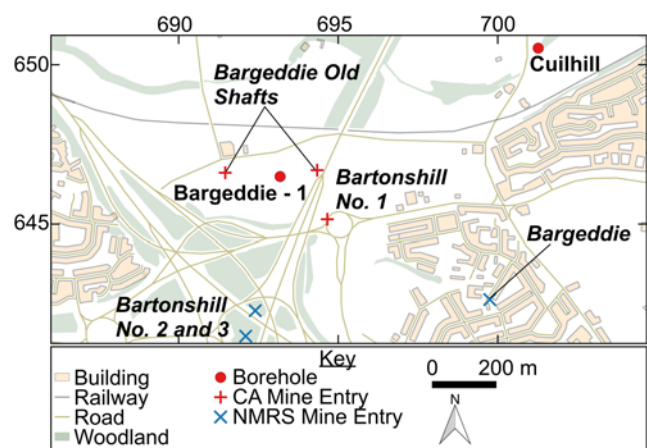


Fig. 13. Map of present-day land use at the locality of the Bargeddie-1 borehole. Location of historical mine entries obtained from the Northern Mine Research Society (NMRS) and the Coal Authority (CA) shown. The coordinates (north and east) are in 500 m intervals within British National Grid 100 km quadrangle NS.

The Cuilhill borehole (Fig. 13), drilled to a depth of *c.* 757 m (BGS Reference: NS76NW345), was used to exert control on the understanding of the subsurface prior to drilling the Bargeddie-1 bore. If this borehole is to be used as analogous to Bargeddie-1, then the position of the seams stated in the Cuilhill borehole can be used to assess the depth of workings close to the Bargeddie-1 borehole. The Cuilhill bore encountered the Main Coal at 50 m, the Splint Coal at 70 m, the Virgin Coal at 72 m and the Kiltongue Coal at 150 m. Shallower seams of Glasgow Upper and Pyotshaw Coal were not encountered, the shallowest seam encountered being the Glasgow Ell Coal. As shown in Figure 13, numerous shafts surround the location of the Bargeddie-1 borehole. It may thus be expected that the temperature gradient may be perturbed in the borehole by the presence of these mine workings. However, given the lack of temperature data across this depth range, no conclusion can be drawn on the potential influence of mining at Bargeddie. The bottom-hole temperature measurement made in the Bargeddie-1 borehole of 39 °C at 1043.6 m is well below the potential influence of mine workings and can be considered a good approximation for the undisturbed thermal state at this depth.

GGC01

Work at the GGERFS aims to investigate the abandoned, flooded mine workings beneath the Clyde Gateway Regeneration area of Glasgow. The GGC01 borehole is the deepest of twelve boreholes drilled in the Clyde Gateway area of Dalmarnock, Glasgow as part of the GGERFS project. Its main purpose is to host seismometers for monitoring earthquake activity, including the possibility of earthquakes caused by activity at the GGERFS site.

The extent of mining in this locality has been summarized by Monaghan *et al.* (2017, 2018). There are seven worked coal seams, with related shafts and interconnecting underground roadways, beneath the area within which the 12 GGERFS boreholes are located (Monaghan *et al.* 2017, 2018). The deepest worked seam beneath this area is the Kiltongue Coal seam which was worked from the Govan No. 5 Pit [NS 60350 62400], however, the depth of this seam varies laterally throughout the area. At its deepest it is encountered at 268.5 m depth (Monaghan *et al.* 2017). At the site of the GGC01 borehole it is predicted to be shallower than this, at around 225 m depth (Monaghan *et al.* 2017).

There are no recorded mine workings on abandonment plans at the site of the GGC01 borehole. After drilling the borehole, it was confirmed that no evidence of mining was encountered in the borehole and several thick intact coals were cored (Starcher *et al.* 2019). However, to the east of the GGC01 borehole there is extensive coverage of mine workings beneath the GGERFS area. Mining activity in this area of Glasgow took place prior to the 1872 Regulation of Coal Mines Act which legislated that accurate mine abandonment plans must be recorded in compliance with the act. It is therefore possible that unrecorded mine workings exist beneath the site of the GGC01 borehole.

From the preliminary driller's log, the deepest coal seam in the GGC01 borehole is thought to be the Airdrie Virtuewell

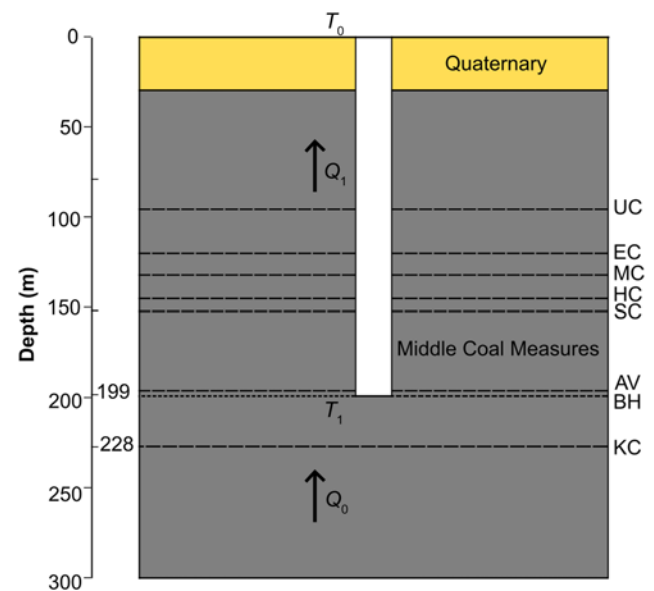


Fig. 14. Schematic log of the GGC01 Borehole [NS 60915 63109] showing summary stratigraphy, including seams worked in the GGERFS area. AV, Airdrie Virtuewell Coal; BH, Bottom Hole; EC, Ell Coal; HC, Humph Coal; KC, Kiltongue Coal; MC, Main Coal; SC, Splint Coal and UC, Upper Coal. Yellow ornament denotes Quaternary deposits. Q_0 denotes the heat flow below mine workings, Q_1 denotes the heat flow above mine workings, T_1 denotes the deepest temperature measurement in the borehole and T_0 denotes the surface air temperature.

Coal at 197 m depth (Barron & Burkin 2019). However, the mined Kiltongue Coal seam is deeper; Kearsley *et al.* (2018) estimate it to lie 31 m below the Virtuewell seam, on which basis we estimate its depth as 228 m (Fig. 14).

From wireline logging of the borehole, a temperature of 14 °C was observed at a depth of *c.* 197 m (Starcher *et al.* 2019). If, as seems likely, the Kiltongue Coal seam was mined beneath the location of this borehole, this legacy of mining may have an influence on the flow of heat in the subsurface and is perhaps a contributing factor as to why the bottom-hole temperature, and associated heat flow, is low in comparison to the regional average.

Discussion

By determining the chronology of historical mining in each borehole locality, the influence of mine workings on subsurface temperature and heat flow has been assessed. While extensive mining was undertaken across much of Glasgow and the surrounding conurbation, the temperature datasets measured at the Blythswood-1, South Balgray, Queenslie-4, Hurlet, Maryhill and Bargeddie-1 boreholes are shown to not be significantly affected by the presence of mine workings. For the Maryhill borehole, the potential influence of mine workings on perturbing the temperature gradient may be counteracted by the influence of surface warming from the Maryhill Ironworks. For the Queenslie-4, Hurlet and Bargeddie-1 boreholes there are no temperature data in the depth range that mine workings may have existed, therefore the potential influence of the workings on the subsurface thermal state is inconclusive. However, the temperature measurements made below the depth of the mine workings are reliable and, alongside the datasets from

Blythwood-1, South Balgray and Maryhill, can be considered good approximations for the undisturbed thermal state beneath Glasgow.

These measurements are therefore suitable for further analysis and can be used when estimating the potential geothermal resource within the deeper HSAs of the Kinnesswood Formation, Knox Pulpit Formation and laterally equivalent sandstones. For example, the temperature gradient can be extrapolated to greater depths, accounting for the changes in thermal conductivity through the stratigraphic sequence, in order to estimate the likely temperature at depth within the HSAs. This is necessary to obtain realistic estimates of thermal performance and drilling costs when appraising future projects. In addition, borehole data can be used when determining the necessary corrections to heat flow to account for the influence of palaeoclimate and topography. This is significant when quantifying the geothermal potential of the HSA resource. As [Westaway & Younger \(2013\)](#) discussed, previous studies of the geothermal potential of the UK have neglected, or underplayed, the correction to heat flow measurements for the cooling effects from periods of lower temperatures during the Pleistocene. This effect is expected to be particularly acute in the UK, due to the large temperature differential between modern times and past ice ages largely a result of the current warming effect of the Gulf Stream. Work on correcting measurements of heat flow in boreholes across the UK, accounting for warming since the last glaciation, has resulted in positive corrections to heat flow ([Westaway & Younger 2013, 2016](#); [Busby *et al.* 2015](#); [Busby & Terrington 2017](#)). A lack of consideration of palaeoclimate corrections has thus resulted in a significant typical underestimate of the heat flow and, therefore, the geothermal potential across the UK. However, definitive correction for palaeoclimate is outside the scope of this work.

At Hallside, the observed temperature dataset appears to be influenced by the legacy of mining at Hallside and Blantyreferme collieries. We propose two potential hypotheses: (A) upward conductive heat flow is greatly reduced above the mine voids as heat is dispersed laterally through the workings ([Fig. 11](#)); and/or (B) downward flow of groundwater through the connected workings is partly cancelling the upward flow of heat. In both cases, the result is a reduced bottom-hole temperature in comparison to the regional average temperature gradient. An effect of historical mining may also be present in the GGC01 borehole temperature record, with flow in mine workings in the Kiltongue Coal seam at depths greater than the base of the borehole providing a natural explanation for the low heat flow and temperature gradient observed in this borehole ([Fig. 14](#)).

As a first-order calculation, we have quantified the heat flow passing into the mine workings beneath the Hallside borehole. Applying the thermal conductivities detailed

in [Table 6](#) to each lithology in the Hallside borehole, the harmonic mean value is calculated as $2.11 \text{ W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$. Based upon meteorological data from the Paisley Coats Observatory (at NS 47395 64223 and 32 m amsl) the annual mean surface air temperature for 1976 was $9.6 \text{ }^{\circ}\text{C}$ ([Met Office 2019](#)); accounting for lapse rate this reduces the surface temperature to $9.45 \text{ }^{\circ}\text{C}$ at Hallside. Combining this value with the bottom-hole temperature at Hallside, the temperature gradient is calculated as $6.68 \text{ }^{\circ}\text{C km}^{-1}$. From [equation \(1\)](#) this gives a heat flow of *c.* 14 mW m^{-2} . If the regional heat flow for Glasgow is taken as 60 mW m^{-2} ([Browne *et al.* 1987](#); [Busby *et al.* 2011](#)), then *c.* 46 mW m^{-2} of heat flow is escaping laterally into the workings below the base of this borehole. As discussed by [Westaway & Younger \(2013\)](#) and [Busby & Terrington \(2017\)](#), if the effect of palaeoclimate is accounted for then the regional surface heat flow for Glasgow may increase to *c.* 80 mW m^{-2} , implying that *c.* 66 mW m^{-2} is entering the mine workings at Hallside.

The same approach can be applied to the GGC01 dataset. [Busby \(2019\)](#) reports the thermal conductivity for the Scottish Middle Coal Measures at the GGERFS as $2.02 \text{ W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$. The annual mean surface air temperature for 2018 is $9.58 \text{ }^{\circ}\text{C}$ at Paisley ([Met Office 2019](#)) and, accounting for lapse rate, this increases to $9.75 \text{ }^{\circ}\text{C}$. Combining this value with the bottom-hole temperature at the GGC01 borehole, gives a temperature gradient of $21.57 \text{ }^{\circ}\text{C km}^{-1}$ which, from [equation \(1\)](#), gives a heat flow of *c.* 44 mW m^{-2} . In accordance with previous discussion, the heat flow escaping laterally into the workings can thus be estimated as between *c.* 16 and *c.* 36 mW m^{-2} depending on whether the effect of palaeoclimate is taken into account or not. On the basis of this simple analysis, the effect of mine workings beneath the GGC01 borehole is less significant than at Hallside.

The Hallside case study provides strong evidence that the conductive heat flow at depths overlying flooded mine workings in the study area has been altered by the existence of these workings and is therefore unrepresentative of the heat flux from the Earth's interior. As observed at Hallside, while the conductive heat flow and associated temperature gradient have been significantly reduced, it may be the case that heat is moving horizontally, carried by groundwater flow, from the workings beneath the borehole to increase temperatures in the mines below other areas of Glasgow. Care must therefore be taken to consider such an effect as this when attempting to quantify the potential geothermal resource in abandoned, flooded mine workings in the future. The entrainment of heat flow into mine workings also affects the quantification of deeper geothermal resources, like the potential HSAs beneath Glasgow. In localities where this effect is present then the extrapolation of the shallow temperature gradient above mine workings would

Table 6. Hallside thermal conductivity values

	Mdst	Sst	Slst	Coal	Lst	Cgl	Strk	Clay	Sand
$k \text{ (W m}^{-1} \text{ }^{\circ}\text{C}^{-1}\text{)}$	1.40^1	4.90^2	2.22^3	0.40^4	2.85^2	2.92^5	1.83^6	1.11^7	0.77^7

¹Bullard & Niblett (1951); ²England *et al.* (1980); ³Downing & Gray (1986); ⁴Herrin & Deming (1996); ⁵Westaway & Younger (2016); ⁶Benfield (1939); ⁷Gale (2004). Mdst, Mudstone; Sst, Sandstone; Slst, Siltstone; Lst, Limestone; Cgl, Conglomerate; Strk, Seatrock.

underestimate the temperature at depth and in a deeper geothermal resource. It is important, therefore, that future projects should consider the influence of historical mining on heat flow when measurements such as this are used as a basis for selecting optimum locations to site a geothermal development.

This present study is particularly timely given the recent development of the UKGEOS GGERFS project in Glasgow and the media attention afforded to the potential geothermal resource in flooded mine workings in the MVS and across former coalfields in the UK. The potential geothermal resource that exists in flooded mine workings has been recognized by many studies (e.g. Leoni 1985; Harrison *et al.* 1989; Hall *et al.* 2011; Ramos & Falcone 2013; Burnside *et al.* 2016a, b; Banks *et al.* 2019) and, indeed, specifically the potential resource throughout the MVS (e.g. Banks *et al.* 2003, 2009; Gillespie *et al.* 2013; Harnmeijer & Schlicke 2016; Harnmeijer *et al.* 2017).

The potential magnitude of the geothermal resource in flooded mine workings in the MVS and across the UK has yet to be fully clarified; however, recent publications have ventured to provide initial estimates of the extractable heat. In the MVS, it is estimated that 12 MW (379 TJ) of heat may be provided from the former Scottish Coalfield (Gillespie *et al.* 2013). More recently Adams & Gluyas (2017) found that across the UK a conservative estimate of the resource in the flooded mine workings is around 38 500 TJ of heat. This would be enough to heat around 650 000 homes.

Conclusion

The MVS is host to two potentially significant geothermal resources: insulated groundwater in flooded abandoned mine workings and HSAs within sandstones of the Kinnesswood Formation, Knox Pulpit Formation and laterally equivalent sandstones. To assess the potential of these resources it is crucial to understand the flow of heat in the subsurface. Studies from the former NE England coalfield in Tyneside have demonstrated heat flow perturbations in boreholes to be the result of lateral dispersion of geothermally radiating heat through flooded mine workings. If this phenomenon is common across flooded mine systems, data obtained from mine-associated boreholes would not be representative of the actual heat flow in the locality. In this work we have investigated the impact of historical mining on geothermal observations across Greater Glasgow by assessing temperature and heat flow records of eight boreholes that are located in areas known to have extensive histories of coal and ironstone mining.

By determining the chronology of historical mining in each borehole locality through an archive study, we have appraised these existing datasets of geothermal measurements. This enables: (1) a quantification of the potential geothermal resource in the abandoned, flooded mine workings; (2) an assessment of the accuracy of existing subsurface temperature measurements, for example as a precursor to applying corrections to heat flow measurements to account for palaeoclimate and topography; and (3) a more accurate extrapolation of subsurface temperature measurements to greater depths. While extensive mining was undertaken across much of Glasgow and the surrounding conurbation,

the temperature datasets measured at the Blythswood-1, South Balgray, Queenslie-4, Hurlet, Maryhill and Bargeddie-1 boreholes are largely unaffected by the presence of mine workings. The measurements in these boreholes are reliable and therefore suitable for further analysis, as described in (2) and (3).

At the GGC01 borehole at the GGERFS, the observed temperature dataset may be influenced by the legacy of mining in the Dalmarnock area of Glasgow. A bottom-hole temperature of 14 °C was recorded at 196.8 m in the GGC01 borehole, resulting in a calculated heat flow of *c.* 44 mW m⁻². The heat flow escaping laterally into the workings can thus be estimated as between *c.* 16 and *c.* 36 mW m⁻² depending on whether the effect of palaeoclimate is considered or not. At Hallside, the observed temperature dataset appears to be influenced by the legacy of mining at Hallside Colliery. A bottom-hole temperature of 11.8 °C was recorded at 352 m in the Hallside borehole, resulting in a calculated heat flow of *c.* 14 mW m⁻². The heat flow escaping laterally into the workings can thus be estimated as between *c.* 46 and *c.* 66 mW m⁻² depending on whether the effect of palaeoclimate is considered or not. The differences relative to the expected regional heat flow suggests a significant component of horizontal heat flow into surrounding flooded mine workings. An examination of the 'true' geothermal resource beneath the city of Glasgow is therefore reliant on an understanding of heat transport mechanisms in the subsurface and care must therefore be taken to consider such an effect as this when attempting to quantify the potential geothermal resource in both abandoned, flooded mine workings and HSAs in the future. Given that the areas of the MVS where the potential geothermal resource is present encompasses two of the largest cities in the UK – Glasgow and Edinburgh – there is a significant potential opportunity of providing low-carbon geothermal heating to areas of dense urban population and high heat demand.

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This work is dedicated to the memory of Paul Younger (1 November 1962–21 April 2018). 'Union miners, stand together, do not heed the owners' tale, keep your hands upon your wages, and your eyes upon the scale.'

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