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Borehole temperature log from the Glasgow Geothermal Energy Research Field Site: a record of past changes to ground surface temperature caused by urban development

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Abstract: As part of the Glasgow Geothermal Energy Research Field Site (GGERFS) project, intended as a test site for mine-water geothermal heat, the GGC-01 borehole was drilled in the Dalmarnock area in the east of the city of Glasgow, starting in November 2018. It was logged in January 2019 to provide a record of subsurface temperature to 197 m depth, in this urban area with a long history of coal mining and industrial development. This borehole temperature record is significantly perturbed away from its natural state, in part because of the 'permeabilizing' effect of past nearby coal mining and in part due to surface warming as a result of the combination of anthropogenic climate change and creation of a subsurface urban heat island by local urban development. Our numerical modelling indicates the total surface warming effect as 2.7°C, partitioned as 2.0°C of global warming since the Industrial Revolution and 0.7°C of local UHI development. We cannot resolve the precise combination of local factors that influence the surface warming because uncertainty in the subsurface thermal properties trades against uncertainty in the history of surface warming. However, the background upward heat flow through the shallow subsurface is estimated as only *c.* 28–33 mW m^{-2}, depending on choice of other model parameters, well below the *c.* 80 mW m^{-2} expected in the Glasgow area. We infer that the 'missing' geothermal heat flux is entrained by horizontal flow at depth beyond the reach of the shallow GGC-01 borehole. Although the shallow subsurface in the study area is warmer than it would have been before the Industrial Revolution, at greater depths – between *c.* 90 and >300 m – it is colder, due to the effect of reduced background heat flow. In future the GGERFS project might utilize water from depths of *c.* 90 m, but the temperature of the groundwater at these depths is maintained largely by the past effect of surface warming, due to climate change and urban development; it is thus a resource that might be 'mined' but not sustainably replenished and, being the result of surface warming rather than upward heat flow, arguably should not count as 'geothermal' heat in the first place. Our analysis thus indicates that the GGERFS site is a poor choice as a test site for mine-water geothermal heat.

Supplementary material: A summary history of coal mining in the study area is available at: https://doi.org/10.6084/m9.figshare.c.4911495.v2

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The Glasgow Geothermal Energy Research Field Site (GGERFS) is a project to provide the subsurface infrastructure to investigate the geothermics of flooded mine workings (e.g. Monaghan *et al.* 2017, 2018). This site is located within the Lanarkshire Basin, a former coalfield in the Midland Valley of Scotland, specifically within rocks of the Scottish Coal Measures Group (Fig. 1) of Upper Carboniferous (Westphalian) age. The GGERFS location is in the Dalmarnock district in the east of the city of Glasgow, north of the River Clyde, also within South Lanarkshire, adjoining the historic town of Rutherglen (Fig. 2). This former coalfield area was also the location of extensive industrial development from the late eighteenth century onwards; most of this has ceased operation, leaving widespread derelict land. Part of the purpose of the GGERFS is indeed to assess the feasibility of minewater geothermal heating (e.g. UKGEOS 2020), the current large-scale redevelopment of the East End of Glasgow (much of it via the Clyde Gateway redevelopment Scheme) providing an opportunity to incorporate this technology into new buildings in the area.

The GGERFS infrastructure consists, first, of a *c.* 200 m deep borehole in Dalmarnock, called GGC-01, drilled at British National Grid reference NS 60915 63109 in November 2018 to January 2019 with British Geological Survey (BGS) ID NS66SWBJ3754, which has been cored and extensively logged (Fig. 3), including for temperature (Kearsey *et al.* 2019; Starcher *et al.* 2019). Second, there are other boreholes, to depths of ≤100 m (e.g. Stephenson 2018; Adams *et al.* 2019), which will initially be used to test the hydraulic properties of individual worked coal seams and might ultimately act as injection or production wells for the recovery of geothermal heat; these are located in the Cuningar Loop of the River Clyde, >1 km east of the GGC-01 borehole (Fig. 2). Detailed plans of the GGERFS project as a whole, including maps, air photos, and cross-sections, are provided elsewhere (e.g. Monaghan *et al.* 2018, figs 1 and 2; Stephenson 2018; Adams *et al.* 2019, figs 3 and 4; BGS 2020).

The aim of this study is to present a first-order analysis of the temperature log from the GGC-01 borehole, to deduce the cause of the subsurface temperature variations thus indicated; this work will be guided by experience of investigating the Science Central well at Newcastle upon Tyne (Westaway and Younger 2016). The analysis will identify causes that relate to the histories of urban and industrial development (Table 1), and of mining (Table 2), in the study area. We shall, therefore, discuss these aspects first, the local stratigraphy being

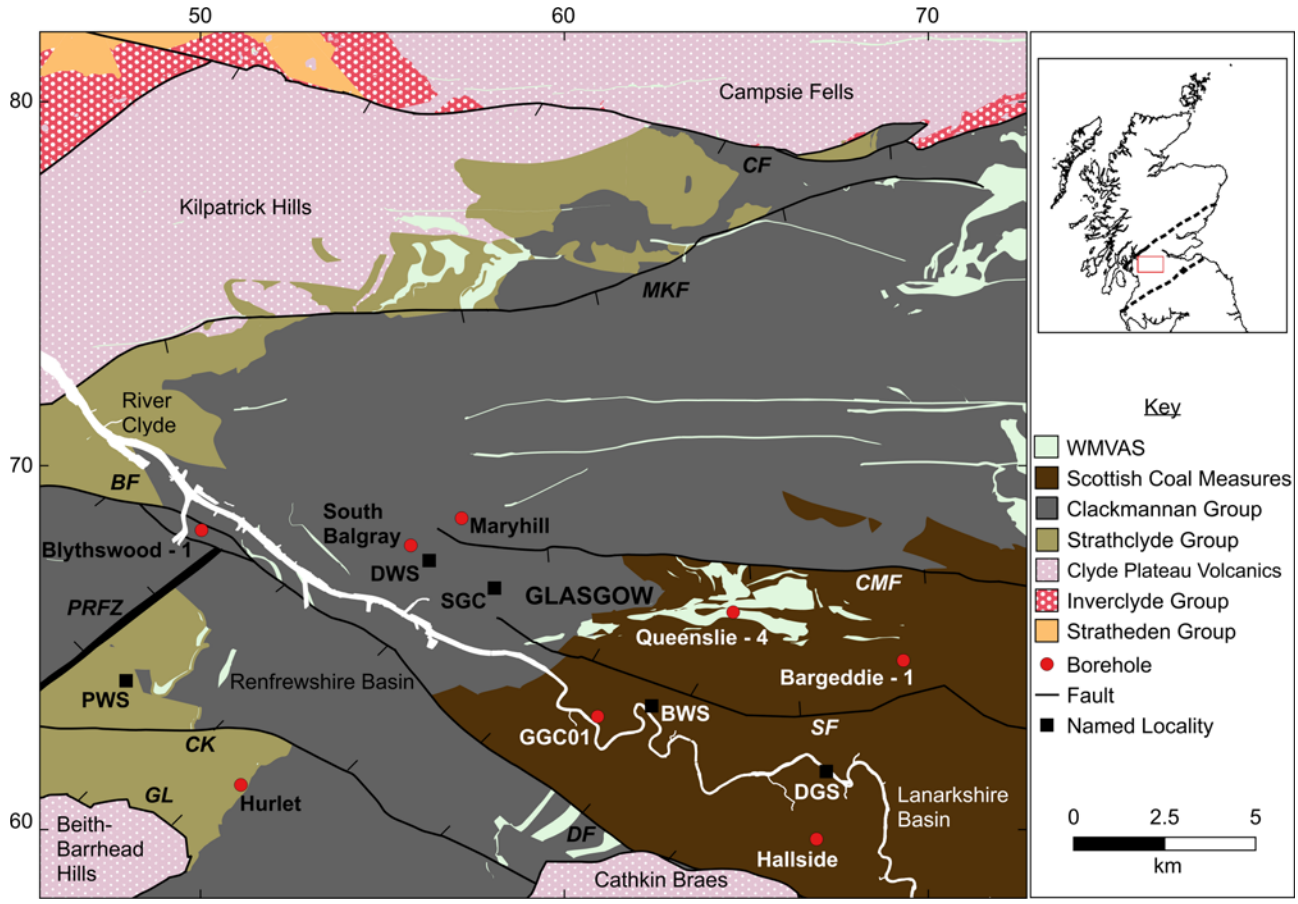


Fig. 1. Simplified solid geology, structure and locations of studied boreholes in Glasgow and the surrounding conurbation, with inset showing location within the Midland Valley of Scotland. WMVAS denotes the Western Midland Valley Westphalian to Early Permian Sills; the local stratigraphy is explained in more detail by Watson *et al.* (2019). Named localities are abbreviated thus: BWS, Belvidere weather station; DGS, Daldowie gauging station on the River Clyde; DWS, Dowanhill weather station; PWS, Paisley weather station; and SGC, St George's Cross Subway station. 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, Glennifer Fault; MKF, Milngavie-Kilsyth Fault; PRFZ, Paisley Ruck Fault Zone; and SF, Shettleston Fault. The coordinates are in kilometres within British National Grid 100 km quadrangle NS.

summarized in Table 3 and the history of mining reported in the online Supplementary material. After presenting the analysis of the borehole temperature dataset, we shall discuss its implications for the geothermics of the area.

History of urban and industrial development

The Dalmarnock area experienced rapid development during the late nineteenth and early twentieth centuries, its form in the 1850s being illustrated in Figure 4 and that in the 1920s–30s in Figures 5 and 6. Guided by previous experience (Westaway and Younger 2016), we document the changes in land use around the GGC-01 borehole site that might have affected ground surface temperatures, to facilitate modelling. This task has involved archival research, investigating sources including Glasgow Valuation Rolls and architectural plans from the City Archives at the Mitchell Library, as well as Post Office and Trade Directories and Ordnance Survey maps spanning the nineteenth and twentieth centuries. The GGC-01 borehole was drilled on land bounded by Martin Street to the east, Norman Street to the west, French Street to the north and Colvend Street to the south. This land was developed at the beginning of the twentieth century (Figs 6 and 7), later cleared and redeveloped (Fig. 8), before being cleared again leaving it vacant at the time of drilling, awaiting further redevelopment. We shall first summarize the history of land use and urban development in the Dalmarnock area, then consider the vicinity of the borehole site in greater detail, concentrating on aspects that might have influenced the ground surface temperature and, thus, the subsurface thermal history.

The Dalmarnock area

Dalmarnock experienced immense changes starting in the late eighteenth century, this area being particularly well placed for industrial development given its proximity to Glasgow and access to the River Clyde (which provided water supply and a means of transport). The textile industry was of particular local importance. In its early stages, this required land for the bleaching of cotton products by sunlight (Hume 1974). Indeed, by the end of the eighteenth century, several bleachfields were located outside the urban area of Glasgow (Adams 1995). Being rural at the time, Dalmarnock was ideally suited for this activity, which required large areas of land; works for spinning, weaving, printing and dyeing textiles also began to develop. The invention of chemical bleach in 1799 eliminated the necessity for bleachfields (Hume 1974). The onset of mechanization and the introduction of steam power resulted in the dramatic expansion of the textile industry on land formerly used as bleachfields (Smart 2002). Urban and industrial

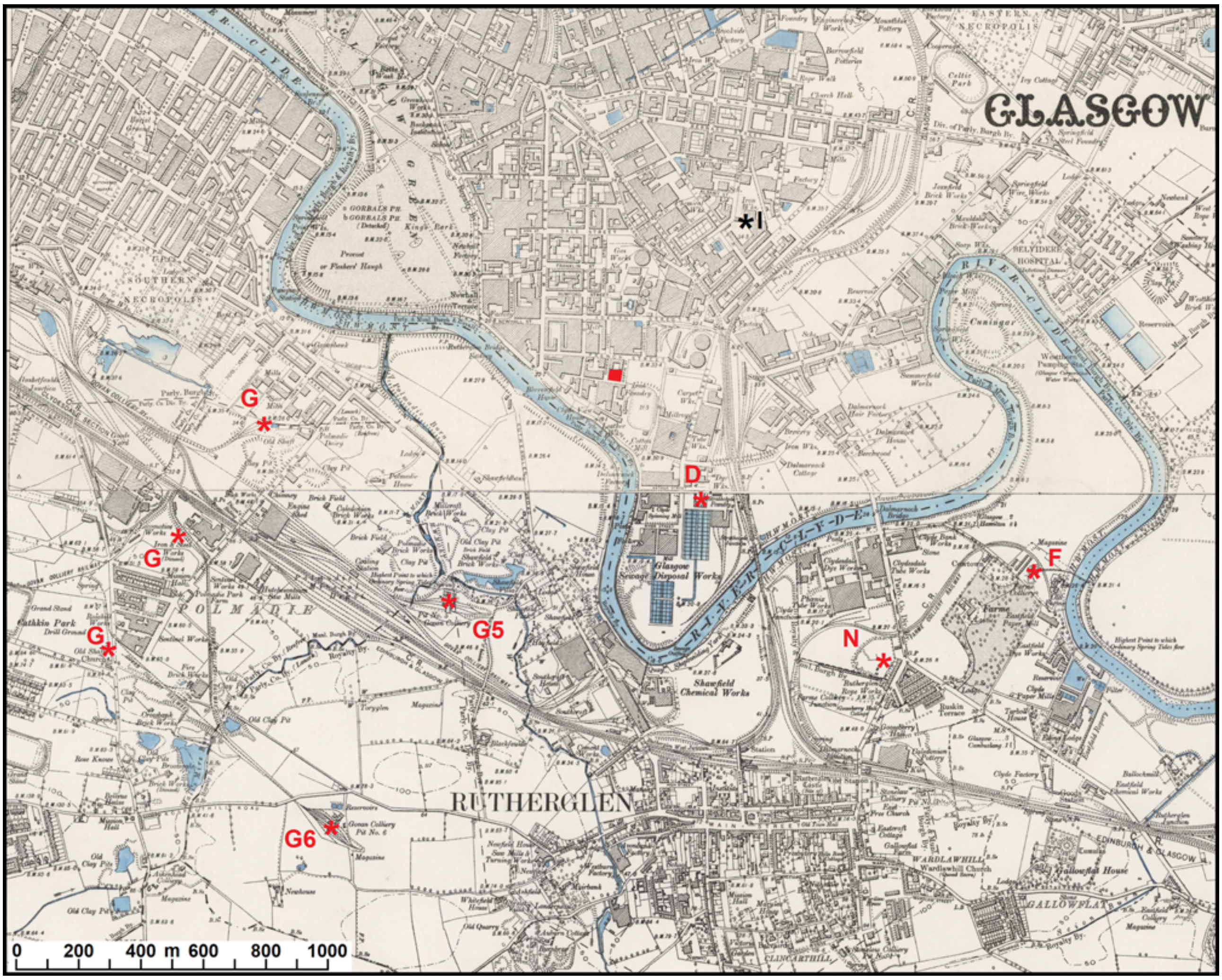


Fig. 2. Depiction of the study area and its surroundings in the 1890s showing the future GGC-01 borehole site (marked by a red square), adjoining industrial premises (details provided in Table 1), which might have caused significant inputs of heat into the subsurface (notably I, the Dalmarnock Iron Works), and mine entries (details provided in Table 2). For the latter, D denotes Dalmarnock Colliery; F denotes Farme Colliery (Old Farme Pit); N denotes New Farme Pit; G5 and G6 denote Pit 5 and Pit 6 of Govan Colliery; and G denotes older pits of Govan Colliery. Cuningar Loop is the northward loop of the River Clyde north of Farme Colliery. Based on excerpts from Ordnance Survey six inches to one mile map sheets Lanarkshire VI.SE (revised 1894; published 1897; https://maps.nls.uk/view/75650661) and Lanarkshire X.NE (revised 1893; published 1898; https://maps.nls.uk/view/75650823); this map imagery is reproduced with the permission of the National Library of Scotland. We note that the district south of the Clyde spanning from east to west across Glasgow was historically known as 'Govan'. Nowadays, this area consists of the NW extremity of South Lanarkshire, known as Shawfield, and the SE extremity of the City of Glasgow, known as Polmadie; nowadays, Govan denotes a district towards the SW extremity of Glasgow.

development continued after Dalmarnock, and the neighbouring districts of Calton and Bridgeton, were absorbed into the City of Glasgow in 1847 (Adams 1995). Industrial premises in the vicinity of the GGC-01 borehole are listed in Table 1 and depicted in Figures 2 and 4–6.

The best known of Glasgow's print and dye works of this era was the Dalmarnock Dye Works, established in 1785 (Wertz 2014; Table 1; Fig. 4). This was the first works in Scotland to specialize in calico printing and Turkey Red dyeing. Turkey Red was a durable dye with a distinctive shade of red, made to a proprietary formula and used to dye cotton products for export worldwide. This process required high temperatures; the printers worked in temperatures of *c.* 27°C and stoves were kept at 60°C where 'webs' of dyed cotton were dried (Smart 2002). Production continued until 1873 when the Turkey Red dye works were demolished, ending Turkey Red production in Glasgow (Wertz 2014).

The Glasgow cotton industry began to decline in the 1850s, due to increased competition, then the lack of imports of raw cotton during the American Civil War (Adams 1995). However, the textile industry persisted as cotton spinning sheds were repurposed for other tasks, such as weaving of carpets and fine quality fabrics (Smart 2002). During the late nineteenth and early–mid-twentieth centuries, engineering works, chemical works, joinery workshops and iron foundries were established to repair and manufacture equipment used by the textile industry, as detailed in Table 1, which also lists other significant industrial premises in Dalmarnock, outside the textile industry. Some operated on a large scale, for example Dalmarnock Iron Works occupied a 20-acre site (NS 61326 63559; I in Fig. 2) and employed up to 5000 people (Smart 2002), producing iron and steel for major bridges. Smaller parcels of land between factories were developed to provide workers' housing in the form of tenement blocks, the form of this area in 1929 being illustrated in Figure 6. Deindustrialization in the 1970s and 1980s saw the demise of many established companies engaged in these 'traditional' industries. The premises that they formerly occupied were

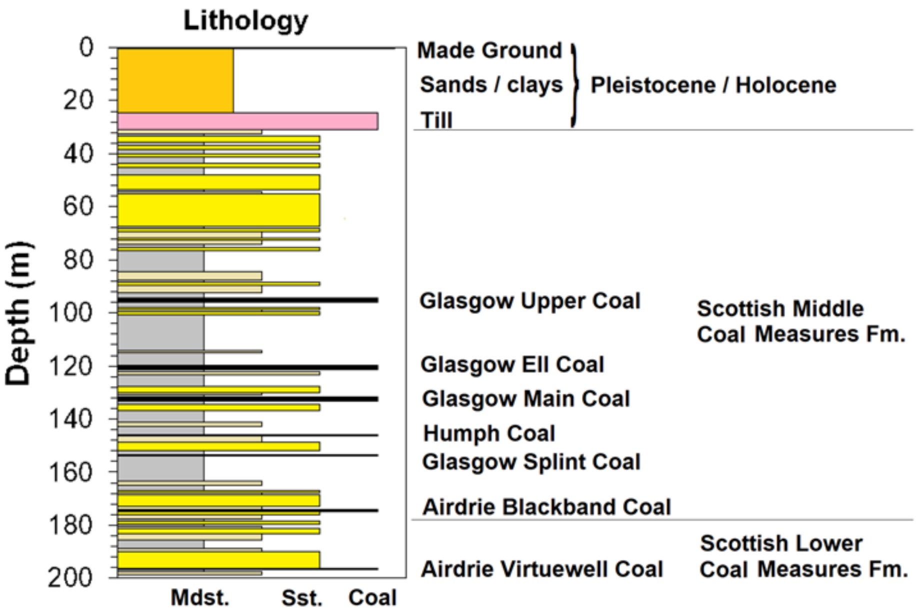


Fig. 3. Simplified lithological log for the GGC-01 borehole. Simplified from Kearsey *et al.* (2019, fig. 2).

then repurposed and split into smaller units including engineering workshops, depots, warehouses and clothing factories (Table 1). By the late twentieth and early twenty-first centuries, many of these buildings had been demolished leaving the land vacant and derelict.

The GGC-01 borehole site

During the early nineteenth century, the site of the future GGC-01 borehole was occupied by bleachfields for the adjacent printing and dyeing works; it is thus depicted in Figure 4. Factory and tenement development later encroached on the surrounding area, but leaving the site itself as an open space. It is thus depicted in Figure 2. In the early twentieth century, four-storey tenement blocks were built on this land. Plans dated 1900 show the proposed construction of 24–36 Martin Street and 79–99 Norman Street (GCA 1900). These buildings, illustrated in Figures 6 and 7, are depicted in the 1912 edition of the local twenty-five inches to a mile (1:2534.4) scale map (https://maps.nls.uk/view/82891800), surveyed in 1910. Land use thereafter remained the same for decades, as shown in Figure 5, the close local community being best known as the base of one of Glasgow's principal street gangs, the 'Norman Conks' (or Norman Conquerors, named after Norman Street) (e.g. Patrick 1973; Godley 2016).

The 1960s and early 1970s saw the demolition of the tenement housing in this area. As Figure 7 shows, by 1968 part of the block between Norman Street and Martin Street had been cleared, but the tenements in its SE corner remained *in situ*. During the late 1960s and early 1970s the Glasgow Valuation Roll records (those for 1965 to 1972 being consulted) state that the addresses 24–36 Martin Street and 79–99 Norman Street changed from occupied as housing to empty premises and then vacant land. By 1972 there is no record within the Glasgow Valuation Roll; it is thus inferred that the Martin Street tenements on and around the future borehole site were demolished in 1971.

This land lay vacant until the 1980s, when a hostel for homeless people with the address 93 Norman Street was built (Glasgow Street Homelessness Review Team 2000; Morrison 2003; Fitzpatrick *et al.* 2010); this first appears on the Glasgow Valuation Roll for 1988. The extent of this building can be seen on a Google Earth image dated 1 January 2002; it covered almost the entire block between Norman Street and Martin Street, the future site of the GGC-01 borehole being beneath a bedroom wing (Fig. 8). Construction details are shown in plans (GCA 1989, 1994); the flooring consisted of 19 mm thick plywood and 80 mm thick styrofoam insulation board between the joists. However, following a change in Scottish Executive policy towards homeless people, a closure programme began in 2003 (Morrison 2003; Fitzpatrick *et al.* 2010). Figure 8, from GlescaPals (2004), shows the hostel building in August 2004 during demolition; a Google Earth image dated 23 April 2005 and another street photo (GlescaPals 2006) dated February 2006 show the cleared site after demolition.

This parcel of land remained unoccupied thereafter by buildings until the start of the GGERFS project. However, as is described in the developer's board meeting minutes (e.g. Clyde Gateway 2011, 2015), from 2011 to 2015 the area was temporarily occupied by showpeople (i.e. seasonal fair-ground workers) who were displaced from other parts of the Clyde Gateway redevelopment area, before being moved on as redevelopment proceeded. The resulting occupation of the site is depicted in Google Earth imagery dated 26 July 2011 and 26 March 2012, images dated 29 April 2011 and 2 April 2015 showing the site before and after. This temporary presence of caravans and trailers is inferred to have not released significant amounts of heat into the subsurface. Following the completion of the GGC-01 borehole, the land around it was landscaped and the adjoining site prepared for re-development, as illustrated in Google Street View imagery dated June 2019.

Subsurface temperatures: Data and analysis

We now explain our procedure for modelling the GGC-01 borehole temperature dataset. To recap: this borehole was

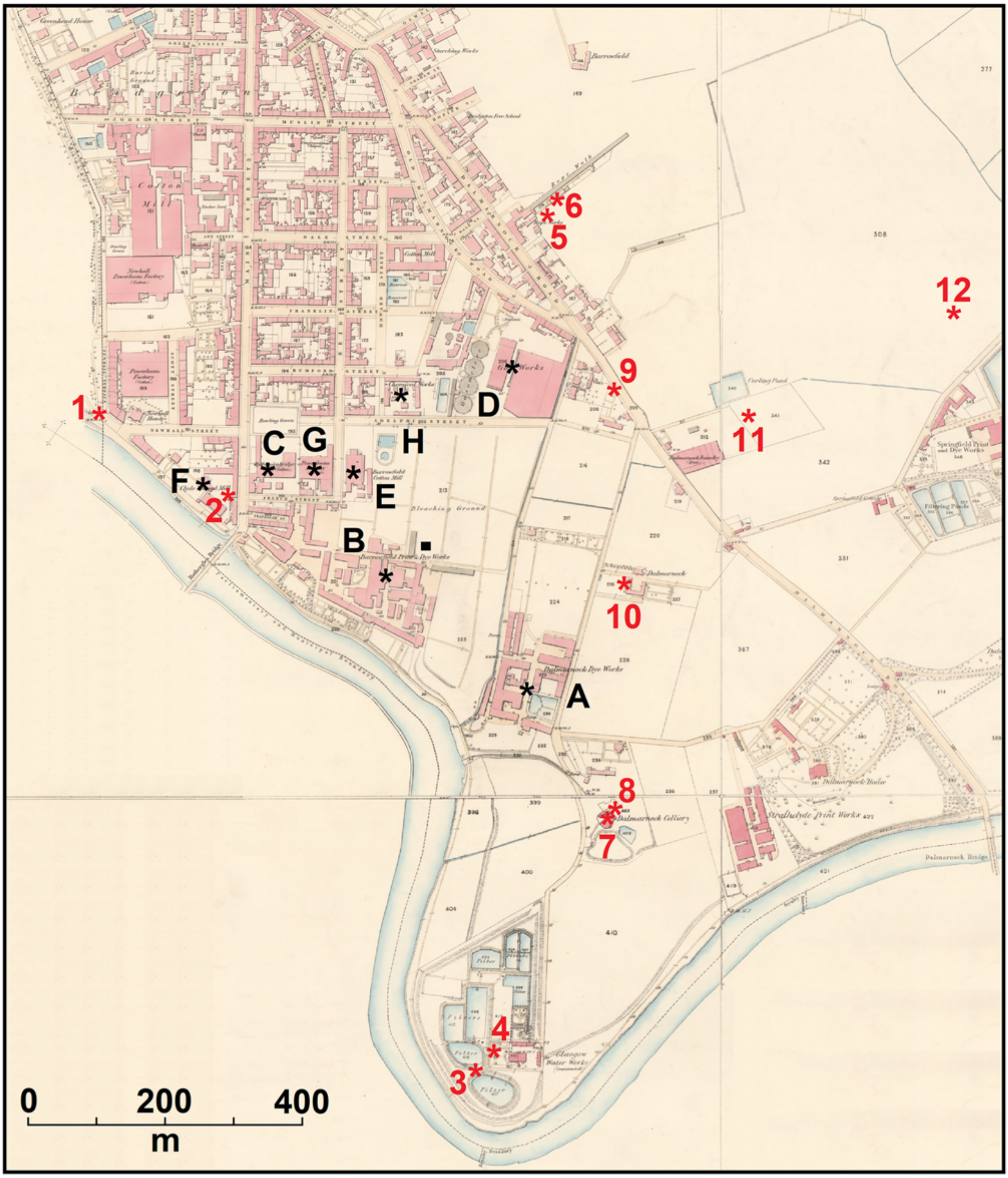


Fig. 4. Depiction of the form of the study area in the 1850s showing the future GGC-01 borehole site (marked by a black square) and adjoining industrial premises (A–H, details provided in Table 1), which might have caused significant inputs of heat into the subsurface, and mine entries (1–12, details provided in Table 2). Based on excerpts from Ordnance Survey twenty-five inches to one mile map sheets Lanarkshire VI.15, Calton (surveyed 1856–58; published 1861; https://maps.nls.uk/view/74952505), Lanarkshire VI.16, Calton (surveyed 1857–58; published 1861; https://maps.nls.uk/view/74952508), and Lanarkshire X.3 (with inset X.4), Calton (surveyed 1857–58; published 1861; https://maps.nls.uk/view/74952511). This map imagery is reproduced with the permission of the National Library of Scotland.

drilled during November 2018–January 2019, temperature being logged in January 2019 (Starcher *et al.* 2019). We first compile the additional data required for this modelling, noting the historical accounts already summarized. We then present two sets of solutions, which encompass the uncertainties involved in the modelling.

Determination of model parameters

We digitized the GGC-01 temperature dataset from the graphical log by Starcher *et al.* (2019). This initial data release was superseded by a more comprehensive version (Kearsey *et al.* 2019), but the temperature graph remained

Table 1 *Industries near the GGC-01 borehole location*

	Name	BNG Reference	Address	Opened	Closed	R (m)	Status	Map	Note
A	Dalmarnock Dye Works	NS 61057 62891	Carstairs Street	1785	1873	260	I	A	1, 2
B	Barrowfield Print and Dye Works	NS 60854 63054	Colvend Street	1802	1873	82	I	A	1, 2
C	Rutherglenbridge Cotton Mill	NS 60687 63229	Main Street	1832	<1892	253	H	A	3
D	Dalmarnock Gas Works	NS 61047 63369	Old Dalmarnock Road	1843	1956	292	C	A, B, C, D	4
E	Barrowfield Cotton Mill	NS 60814 63219	Reid Street	1846	>1970	149	C	A, B, C, D	4
F	Clyde Thread Mill	NS 60594 63211	Main Street	1854	1955	337	I	A, B, C, D	4
G	Powerloom factory	NS 60758 63227	Reid Street	<1858	<1892	196	I	A	
H	Chemical works	NS 60887 63333	Adelphi Street	<1858	<1905	266	I	A, B	
I	Barrowfield Finishing Works	NS 60762 63154	French Street	1880	1930	159	I	B, C, D	
J	Barrowfield Oil and Colour Works	NS 60830 63130	French Street	1880	1930	88	I	B, C, D	4
K	Crown Chemical Works	NS 60798 63055	Colvend Street	1880	1940	129	I	B, C, D	4
L	Barrowfield Leather Works	NS 60874 62967	Colvend Street	1880	<1930	148	I	B, C, D	4
M	Barrowfield Weaving Factory	NS 60945 63222	French Street	1890	1950	135	I	B, C, D	4
N	Clyde Carpet Works	NS 61209 63029	Swanston Street	<1892	<1930	305	I	B, C	
O	Tube Works	NS 61190 62952	Swanston Street	<1892	>1970	317	I	B, C, D	
P	Dalmarnock Factory	NS 61025 62774	Swanston Street	<1892	<1960	353	I	B, C, D	
Q	Iron Foundry	NS 60910 63051	Colvend Street	<1892	>1934	58	I	B, C, D	
R	Barrowfield Cotton Mill	NS 61066 62897	Carstairs Street	1895	1925	260	I	B, C	

This table lists industrial premises that opened before 1900, within a 400 m radius (R) of the GGC-01 borehole. Status denotes: I, site reused by other industry after this business closed (including, for entries A and B, other businesses listed in this table); H, site reused for housing after this business closed; and C, site cleared after this business closed. Map denotes editions of twenty-five inches to one mile maps that show the business, or the same building used by another business after the original use came to an end: A, from 1858; B, from 1892; C, from 1910; and D, from 1934. The data summarized are mainly from annual Post Office Glasgow directories, prepared by the Glasgow Post Office Directory Association and published before 1905 by Mackenzie, Glasgow, and subsequently by Bell, Aird & Coghill Ltd, Glasgow. Notes: 1, street not defined at the time; 2, the Turkey Red dye works that we have labelled A and B both date from the late eighteenth or early nineteenth centuries. That labelled A was known in the early nineteenth century as the Dalmarnock Dye Works, whereas that labelled B was known as 'Messrs. Henry Monteith, Bogle, & Co.'s Works' (e.g. Cleland 1816, v. 2, p. 154, this author noting both these works in 1813). Contemporary sources (e.g. Cleland 1840, p. 90; Doskey, 1988, p. 717) and some recent sources (e.g. Campbell 1995) indicate that B denotes the works founded by Henry Monteith and partners in 1802; we thus infer that A is the works originally founded by David Dale and George Macintosh in 1785. However, other sources (e.g. Peel 1952; Hume 1974; Adams 1995; Wertz 2014) are less clear about this. In 1805 Dale and Macintosh sold their works to Monteith and, thereafter, both were operated until closure in 1873 as a combined business (Peel 1952); changes in name of individual works and expansion of premises complicate the story. Other data sources are indicated by: 3, Headland (1980); and 4, Hume (1974).

exactly the same. These data releases indicate that temperature was measured using a semiconductor probe. Such devices are typically precise to <0.01°C and accurate to <0.02°C (e.g. Analog 2017; Michalski and Klitzsch 2018); the digitization did not contribute significantly to the error budget. No values for thermal conductivity k or thermal diffusivity κ for this stratigraphic succession (Fig. 3 and Table 3) have been reported. We therefore digitized the stratigraphic log from Kearsey *et al.* (2019) and used experience of the thermal properties of the lithologies (e.g. Westaway and Younger 2016; Table 4) to determine harmonic mean values of k and κ. For the succession as a whole (Fig. 3), we thus obtained k=1.60 W m^{-1} °C^{-1} and κ=0.77 mm^2 s^{-1}. Treating its parts separately, we obtained k=1.10 W m^{-1} °C^{-1} and κ=0.48 mm^2 s^{-1} for its Pleistocene/Holocene part and k=1.77 W m^{-1} °C^{-1} and κ=0.88 mm^2 s^{-1} for its Carboniferous part. However, some beds in this succession consist of fine-scale interdigitation of different lithologies, such as sandstone and mudstone, requiring estimation of their thermal properties and creating some uncertainty in these results.

Table 2. *Mine entries in the Dalmarnock area*

No.	Name	BNG	Depth (m)	Notes
1	Rutherglen Old Shaft	NS 60444 63318	–	
2	Rutherglen Old Shaft	NS 60629 63193	198	
3	Dalmarnock Old Shaft	NS 60981 62333	–	
4	Dalmarnock Old Shaft	NS 61010 62360	–	
5	Rutherglen Ruby Shaft	NS 61108 63593	–	
6	Dalmarnock Old Shaft	NS 61124 63614	–	
7	Dalmarnock Engine Shaft	NS 61181 62715	150	1
8	Dalmarnock No 2 Shaft	NS 61192 62717	–	
9	Blind pit	NS 61198 63331	–	2
10	Dalmarnock Old Shaft	NS 61203 63042	–	
11	Old Shaft	NS 61388 63278	–	
12	Old Shaft	NS 61677 63426	–	

Data are from the Coal Authority online viewer (https://mapapps2.bgs.ac.uk/coalauthority/home.html), coordinates being provided as British National Grid (BNG) references to the nearest metre. Notes indicate:1, Dalmarnock Colliery, or Dalmarnock No. 1 Pit, as described in the text.2, Blind pit (i.e. a shaft between coal seams, not reaching the Earth's surface) connected underground with the Dalmarnock No. 1 Pit.

For comparison, Busby (2019) investigated the record from borehole Cuningar Loop M7 (NS66SW17585/M7, at NS 624 626), in which a 38.25 m succession through the Scottish Middle Coal Measures Formation was logged. Using a set of representative values for the lithologies present, he determined the harmonic mean thermal conductivity for this succession as 2.02 W m^{-1} °C^{-1}. However, 2.11 m of this succession spanned a worked coal seam that had been infilled with spoil, for which a nominal thermal conductivity of 1.7 W m^{-1} °C^{-1} was assumed. Had this interval not been mined, so coal with a thermal conductivity of *c.* 0.4 W m^{-1} °C^{-1} were present, the harmonic mean thermal conductivity for the succession would have been 1.67 W m^{-1} °C^{-1}, very similar to our own estimate for the GGC-01 borehole, *c.* 1.6 km farther WNW.

The GGC-01 temperature log (Starcher *et al.* 2019) indicates a near-surface temperature of 11.2°C. Temperature falls below 11°C at depths of *c.* 12–14 m, then rises gradually to 14.0°C at 197 m. As will become clear, our best estimate of the annual mean ground surface temperature at this site is 10.7°C; the relatively high temperatures at shallow depths indicate a subsurface Urban Heat Island (UHI). From previous experience (e.g. Banks *et al.* 2009; Westaway and

Table 3. *Stratigraphy of the study area*

	Govan No. 5 Pit			Dalmarnock Colliery			Borehole GGC-01			
	H (m)	Worked?	Z (m)	H (m)	Worked?	Z (m)	Z_1 (m)	Z_2 (m)	H (m)	Notes
Glasgow Upper Coal	1.37	Yes	131	1.35	Yes	89	80	96	1.5	1
Glasgow Ell Coal	0.99	Yes	157	1.37	Yes	114	109	121	1.3	1
Musselband Ironstone	ND	ND	ND	0.18	No	119	112	127	ND	
Glasgow Main Coal	1.47	Yes	168	1.52	Yes	124	116	133	1.5	1
Humph Coal	0.91	Yes	186	0.61	Yes	138	136	147	ND	
Splint Ell Coal	1.12	Yes	195	ND	ND	ND	ND	ND	ND	
Splint Main Coal	1.19	Yes	199	0.76	Yes	147	147	154	0.6	
Virgin Coal	0.46	Yes	200	0.38	No	148	151	ND	ND	1
Airdrie Blackband Coal	ND	ND	ND	0.62	No	173	175	ND	ND	
Queenslie Marine Band	ND	No	ND	ND	No	ND	180	ND	ND	2
Airdrie Virtuewell Coal	ND	Yes	ND	0.20	No	185	187	197	0.4	1
Sandstone beds	ND	No	ND	8.84	No	214	216	NR	NR	
Kiltongue Coal	ND	Yes	259	0.38	No	215	218	NR	NR	
Lime Coal	0.03	No	265	0.14	No	222	ND	NR	NR	
Upper Drumgray Coal	0.36	No	275	0.23	No	229	ND	NR	NR	
Mid Drumgray Coal	0.25	No	281	0.34	No	234	ND	NR	NR	
Sandstone beds	2.18	No	284	7.92	No	246	ND	NR	NR	
Lower Drumgray Coal	0.08	No	284	0.10	No	248	ND	NR	NR	
Sandstone beds	1.17	No	286	3.12	No	253	ND	NR	NR	
Shotts Gas Coal	0.52	No	287	NA	No	NA	ND	NR	NR	
Shiels Coal	0.13	No	290	NA	No	NA	ND	NR	NR	
Sandstone beds	3.64	No	293	NA	No	NA	ND	NR	NR	
Mill Coal	0.22	No	296	NA	No	NA	ND	NR	NR	
Sandstone beds	1.98	No	300	NA	No	NA	ND	NR	NR	
Balmoral Index Coal	0.60	No	303	NA	No	NA	ND	NR	NR	

Comparison of the stratigraphy in the shafts of the No. 5 Pit of Govan Colliery and Dalmarnock Colliery, with GGERFS borehole 10. Stratigraphic data, including thickness H and basal depth Z, for Govan No. 5 Pit (at NS 60347 62392) are from the online shaft logs (records NS66SW179 and NS66SW198, dating from 1868, for the upper part down to the Sour Milk Coal; record NS66SW197, dating from 1914, for the part below the Kiltongue Coal). Stratigraphic data for Dalmarnock Colliery are from online log NS66SW236. Data between the surface and the Splint Coal are from the log of the shaft (at NS 61181 62715); data from greater depths are from an exploratory boring *c.* 6 m further east. Unfortunately, one scanned page of this obliterates part of another; as a result, the deeper part of the record is not legible and is listed as 'not available' (NA). Data for borehole GGC-01 (NS66SW3754; NS 60915 63919) are from Starcher *et al.* (2019). Z_1 denotes the depth anticipated in the BGS pre-drilling prediction, obtained by adding the predicted depth below OD to the surface level, reported as 9.66 m OD, which is rounded to 10 m. Z_2 denotes the depth encountered by drilling. ND denotes 'not determined'; NR denotes 'not reached by drilling'. Notes denote: 1, Comparison between modern and historical nomenclature for coal seams is based on McLean (2018). Historically, these seams are known as the Mossdale, Rough Ell, Rough Main, and Sour Milk coals. 2, The Queenslie or Vanderbeckei Marine Band defines the base of the Scottish Middle Coal Measures Formation (e.g. Hall *et al.* 1998).

Younger 2016) we interpret this subsurface UHI as a consequence of past downward flow of heat into the subsurface as a result of urban activity. The GGC-01 temperature log will thus be modelled subject to the assumption that subsurface temperature change at this site, like at similar sites previously investigated (e.g. Westaway and Younger 2016), is a consequence of changes in surface temperature, which cause downward (i.e. one-dimensional) conduction of heat. Under this assumption, pulses of heat caused by changes in surface temperature diffuse downward, each producing a peak effect at depth z_M at time t_M later, where $t_M = z_M^2/(4\,\kappa)$ (e.g. Westaway and Younger 2016). Thus, with κ=0.77 mm^2 s^{-1} (see above), z_M=100 m indicates t_M=103 years and z_M=150 m indicates t_M=231 years. It is thus to be expected that a temperature log on the vertical scale of the GGC-01 record largely reflects surface temperature changes since the Industrial Revolution and, therefore, urban development. Given the winter timing of the GGC-01 temperature measurement, the downward temperature fall in the shallow subsurface is consistent with the expected seasonal variation in surface temperature; it can be readily modelled as such (see below). However, at greater depths the mean temperature gradient of only 16°C km^{-1} (*c.* 3°C temperature rise across 185 m distance to 199 m depth) would imply a steady-state geothermal heat flow of only *c.* 24 mW m^{-2}. The raw heat flow in the Glasgow area is *c.* 60 mW m^{-2} (e.g. Busby *et al.* 2011), but can be expected to adjust to *c.* 80 mW m^{-2} after correction for palaeoclimate (Westaway and Younger 2013; Busby and Terrington 2017). For example, Watson *et al.* (2020) have shown that the measured heat flow of 63 mW m^{-2} in the Maryhill Borehole in NW Glasgow (Fig. 1) indicates 80 mW m^{-2} after correction for palaeoclimate. Based on previous experience (e.g. Westaway and Younger 2016) we infer the low geothermal gradient measured in the GGC-01 borehole to be at least in part because the natural upward flow of geothermal heat is being partly cancelled by downward heat flow caused by surface warming. Nonetheless, our experience (Westaway and Younger 2016; Watson *et al.* 2019) indicates that other factors may also influence subsurface temperature in a former coalfield, notably effects of heat transport by fluid flow.

Mining at Dalmarnock Colliery is inferred to have taken place between depths of 96 and 147 m (Table 3); this was between 1824 and 1859 or 194–159 years before the GGC-01 temperature measurement (see the online Supplementary material). However, the GGC-01 site is *c.* 400 m west of the area where coal mining is known to have occurred, from mine plans, in an area where Monaghan *et al.* (2017) regarded mining, of the Upper, Ell, Main and Splint seams, as 'probable'. Monaghan *et al.* (2017) inferred 'probable' extents of mining, such as this, on the basis of voids

Fig. 5. Depiction of the form of the study area in the 1930s showing the future GGC-01 borehole site (marked by a red square) and adjoining industrial premises (details provided in Table 1), which might have caused significant inputs of heat into the subsurface. Based on excerpts from Ordnance Survey twenty-five inches to one mile map sheets Lanarkshire VI.15 (revised 1934; published 1935; https://maps.nls.uk/view/82891803), Lanarkshire VI.16 (revised 1934; published 1935; https://maps.nls.uk/view/82891812), Lanarkshire X.3 (revised 1935; published 1936; https://maps.nls.uk/view/82892259), and Lanarkshire X.4 (revised 1934; published 1936; https://maps.nls.uk/view/82892271). This map imagery is reproduced with the permission of the National Library of Scotland.

(representing worked coal seams) reported during drilling. Nonetheless, it is unclear from this study which deep borehole(s) might have indicated such evidence. Nor is it clear from this study which mine shaft in this area coal might have been extracted. It might possibly have been one of those adjoining the River Clyde near Rutherglen Bridge (1 or 2 in Table 2 and Fig. 4), although we have been unable to find any records of mining in either locality, suggesting that it may have occurred before 1850 when reporting of mine plans became a regulatory requirement (e.g. Westaway and Younger 2016). Indeed, the 198 m shaft depth at pit 2 is consistent with the disposition of the Virtuewell Coal by comparison with the nearby Govan No. 5 Pit (Ellen *et al.* 2013; Fig. 2; see also the online Supplementary material). The GGC-01 data releases (Starcher *et al.* 2019; Kearsey *et al.* 2019) include a 'pre-drill prognosis' diagram, prepared

Fig. 6. Oblique air photo, dated 29 May 1929, looking northward across Dalmarnock including the vicinity of the future GGC-01 drilling site. The River Clyde is in the foreground and Dalmarnock Gas Work in the top right. The east–west streets visible are, from the foreground, Colvend Street, French Street and Adelphi Street. The large flat-roofed buildings are the Clutha Weaving Factory (south of Colvend Street) and the Barrowfield Weaving Factory (north of French Street). Between Colvend Street and French Street, near the centre of the view, are three roughly square street blocks, formed of tenement buildings, bounded from east to west by Carstairs Street, Rockcliffe Street, Martin Street and Norman Street, the GGC-01 borehole being now located near the SE corner of the most westerly of these blocks near the junction of Colvend Street and Martin Street. Image SC 1256829, from http://canmore.org.uk/collection/1256829, used with permission.

ahead of the drilling, showing five coal seams (the Upper, Ell, Main, Humph and Splint seams) as 'probable workings', rather than the four of Monaghan *et al.* (2017), also another diagram and some text, prepared after the drilling, reporting the coal seams transected by the borehole as intact, with no evidence of mining. This text added that mine workings in these seams had previously been considered 'possible' (rather than 'probable') based on the records of mining to the east of the site, with no mention of any evidence from previous drillings encountering voids in worked coal seams, the evidence on which the Monaghan *et al.* (2017) interpretation had reportedly been based.

Watson *et al.* (2019) investigated the subsurface temperature dataset at Hallside, SE of Glasgow (Fig. 1); a BGS geothermal borehole was located here above disused mine workings. Watson *et al.* (2019) estimated the heat flow through this borehole as 14 mW m^{-2}, implying (if the heat flow at depth is *c*. 80 mW m^{-2}, as at Maryhill) that heat flow equivalent to *c*. 66 mW m^{-2} is locally entrained by horizontal flow within the mine workings at a depth greater than is reached by the borehole. Westaway and Younger (2016) had previously estimated that a large proportion of the heat flow from depth, sampled by the Science Central borehole in Newcastle upon Tyne in NE England, is analogously entrained by flow within mine workings, However, here the entrainment is concentrated at a depth of *c*. 160 m, corresponding to one of the formerly worked coal seams, within the depth span of the borehole. In this locality, by 'permeabilizing' the sediments the mining has fundamentally altered the thermal state of the shallow crust away from its natural form, the present thermal state reflecting changes since the modification took place and retaining no 'memory' of the former thermal state before mining began.

We infer that something similar has happened, following the start of deep mining, in the Dalmarnock area. Given the historical evidence already summarized, we take the effective start of the deep mining as the year 1771, or 247 years before the temperature measurement. We assume that the relatively low heat flow at depths of <200 m arises because of entrainment of much of the geothermal heat flux into permeable rock layers (sandstone and/or worked coal seams) at a greater depth (too deep to be registered by the GGC-01

Fig. 7. Photograph, dated 2 August 1968, showing the view looking SE towards Martin Street. On the right can be seen the backs of the three tenement buildings comprising numbers 24–36 Martin Street, on the west side of this street; on the left, numbers 5–21, on the east side of the street, are also visible. The present GGC-01 borehole is beneath the location of the middle of the three tenement buildings on the west side of the street. Image SC 685801, from https://canmore.org.uk/site/204236/glasgow-5-21-odd-martin-street-tenements, used with permission.

Fig. 8. View looking southward along Martin Street from French Street towards Colvend Street in August 2004. On the right of the view, the Norman Street shelter for homeless people is visible: the more distant bedroom wing, facing Colvend Street, overlies the future site of the GGC-01 borehole; demolition of the nearer wing, facing French Street, is already underway. Image from the GlescaPals website (from http://www.glesga.ukpals.com/streets/martinst.htm), used with permission.

Table 4. *Thermal properties*

	k		c		ρ		κ
Lithology	(W m^{-1} °C^{-1})	Note	(J kg^{-1} °C^{-1})	Note	(kg m^{-3})	Note	(mm^2 s^{-1})
Clay	1.11	1	860	5	2680	5	0.482
Sand/Gravel	0.77	1	860	5	1900	6	0.334
Coal	0.40	2	1300	5	1350	5	0.228
Limestone	2.85	3	880	5	2760	5	1.173
Mudstone	1.41	4	770	6	2600	6	0.704
Sandstone	4.54	4	930	6	2460	7	1.984

k, thermal conductivity; *c*, specific heat capacity; *ρ*, density; *κ*, thermal diffusivity. These are interrelated via the formula $k \equiv \rho\, c\, \kappa$, which is used here to calculate *κ*. Notes denote sources of data: 1, Gale (2004), 2, Herrin and Deming (1996), 3, England *et al.* (1980), 4, Wheildon *et al.* (1985), 5, Waples and Waples (2004), 6, Robertson (1988); and 7, Westaway and Younger (2016). Made ground is assumed to have the same thermal properties as sand/gravel. The specific heat capacity of sand/gravel is assumed to be the same as for clay.

borehole) leaving no 'memory' of the pre-mining thermal state. We also infer that at shallower depths the thermal state is now governed by surface temperature changes, caused by the combination of global warming and effects of buildings at the site.

Modelling solutions

We now model the GGC-01 temperature record quantitatively on this basis. *A priori*, we do not know whether the observed temperature variations are caused solely by conduction or in part by fluid flow, nor whether the causative subsurface heating effects reflect the surface temperature history of the site itself or of the general vicinity. We start by assuming purely site-specific effects. In principle, we might use the plans (which we found in the city archive, as already noted) to build models for the former homeless people shelter and tenement building at the site, using software such as Plan Assessor (NHER 2014) that calculates the energy efficiency of buildings, to determine temperature changes at ground level beneath these buildings caused by their energy use. We instead assume that the buildings each caused a temperature rise, ΔT_O, while they were occupied, adjusting these values to match the data. Given earlier discussion, we estimate occupation from late 1988 to late 2003 for the homeless people shelter, or between 30 and 15 years before the temperature measurement, and from late 1900 to late 1970 for the tenement building, or between 118 and 48 years before this measurement.

Subject to the above set of assumptions, the surface temperature history depicted in Figure 9a results in the present-day geotherm depicted in Figure 9b. The prediction in Figure 9b also assumes the calculation procedure of Westaway and Younger (2013) and a thermal diffusivity κ of 0.9 mm^2 s^{-1} representing the Carboniferous bedrock, superimposed on a steady-state geotherm characterized by a surface temperature of 10.7°C, steady-state heat flow of 32.7 mW m^{-2} and thermal conductivity k=1.8 W m^{-1} °C^{-1}. The corresponding seasonal temperature effect is modelled after Westaway and Younger (2016) assuming a sinusoidal variation in surface temperature of amplitude ΔT_S=4°C, a seasonal phase angle corresponding to midwinter and a thermal diffusivity of 0.6 mm^2 s^{-1} representing the Pleistocene deposits in the uppermost *c.* 30 m of the section (Fig. 1). This solution has been designed to represent the assumption that downward heat losses from the buildings that formerly occupied the GGC-01 site make the only contribution to anthropogenic subsurface heating at the site, their respective heat losses (represented by the parameter ΔT_O), being adjusted to match the measurements.

Figure 10 shows an alternative solution; the surface temperature history depicted in Figure 10a results in the present-day geotherm depicted in Figure 10b. This prediction uses the same calculation procedure as for Figure 9, the Carboniferous bedrock now assumed to have k=1.6 W m^{-1} °C^{-1} and κ=0.7 mm^2 s^{-1}, the other input parameters being the same as for Figure 9 except that the steady-state heat flow has been adjusted to 28.2 mW m^{-2}. This solution has been designed to represent the assumption that the downward heat flow has arisen in part from the buildings that formerly occupied the GGC-01 site and in part from local industrial

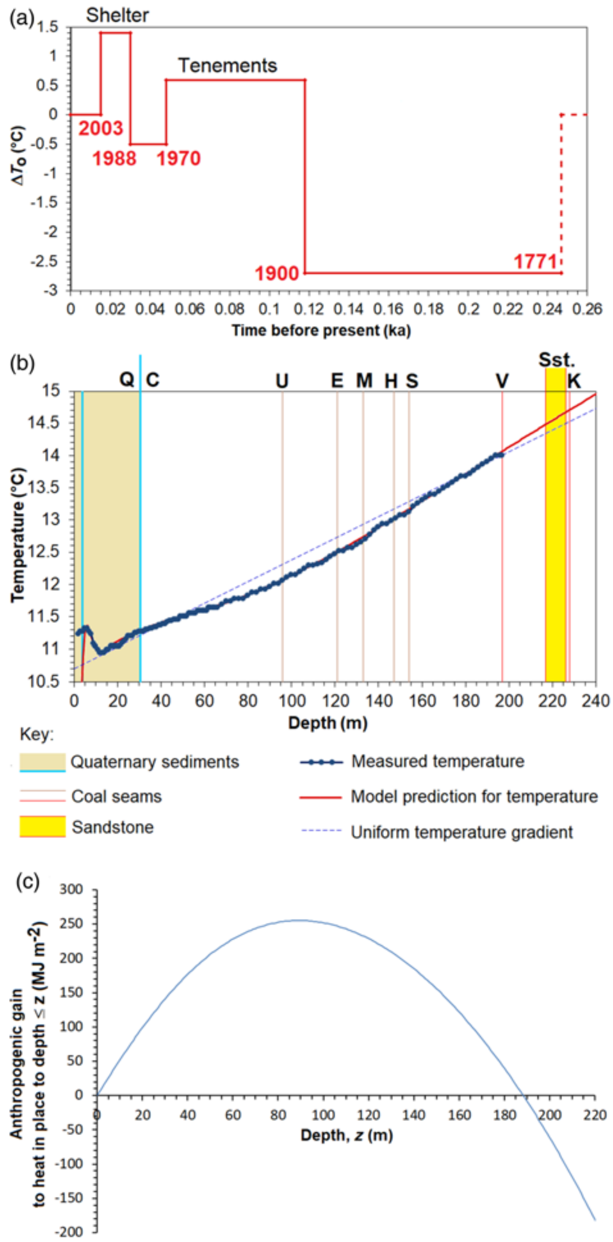


Fig. 9. First solution for subsurface temperature modelling. (**a**) Assumed surface temperature history, expressed as the assumed temperature difference ΔT_O relative to the current surface temperature for 2018–19, the time of temperature measurement. (**b**) Comparison between subsurface temperature data (solid symbols) and model prediction for the surface temperature history in (a) (thick solid line), calculated as explained in the main text. Dashed line indicates the steady-state geotherm between a surface temperature of 10.7°C and the well bottom, at a geothermal gradient of 16.8°C km^{-1}. Boundary Q–C denotes the unconformity between Quaternary (Pleistocene–Holocene) and Carboniferous rocks, the Quaternary rocks being shaded. Other letters above vertical lines denote coal seams, at depths listed in Table 3: U, Glasgow Upper Coal; E, Glasgow Ell Coal; M, Glasgow Main Coal; H, Humph Coal; S, Splint Coal; V, Airdrie Virtuewell Coal; and K, Kiltongue Coal. Label SSt., with shading, indicates the thick sandstone bed above the Kiltongue Coal (Table 3). (**c**) Estimated subsurface heat in place. This graph peaks at a depth of 89 m, corresponding to the depth at which the modern geotherm crosses the estimated pre-Industrial Revolution geotherm in Figure 12. See text for discussion.

premises, the latter contribution being assumed to have begun 175 years before the temperature measurement, in the year 1843, this being the date when Dalmarnock Gas Works began operation (Table 1). Coal gas or 'town gas' was

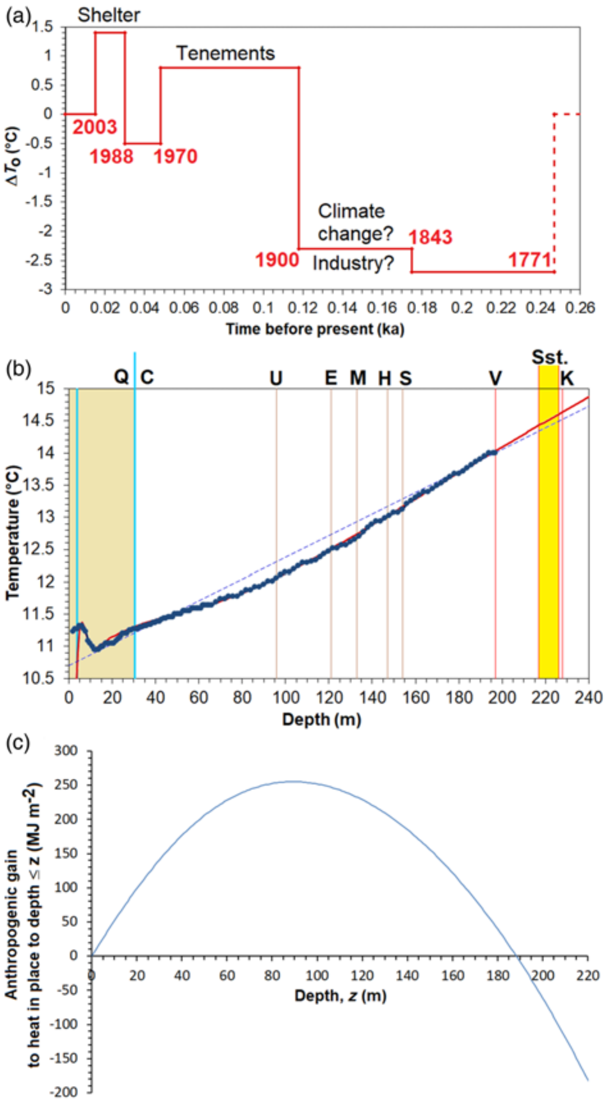


Fig. 10. Second solution for subsurface temperature modelling, with the same display format as Figure 9; see text for discussion. The graph in (**c**) peaks at a depth of 75 m, which differs from that in Figure 9c due to the different choice of values for input parameters.

produced at this and other installations by heating coal to temperatures of *c.* 400°C by burning other coal as a fuel. This relatively energy-intensive activity (cf. Westaway *et al.* 2015) is likely to have released more energy into the subsurface than other industries in the vicinity, with the possible exception of the various iron works (cf. Westaway and Younger 2016).

Effects of climate change and UHI development

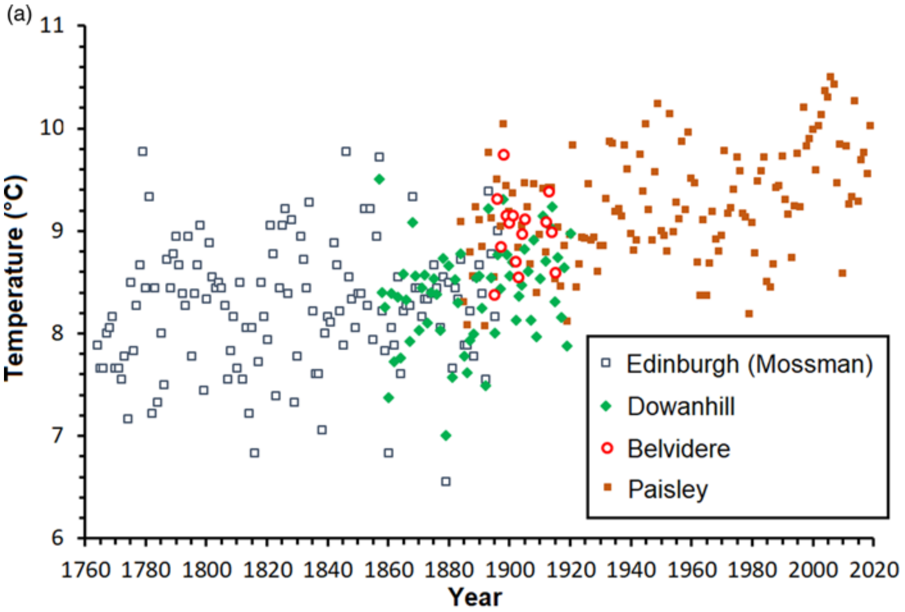
We now consider how the *c.* 2.7°C net rise in ground surface temperature at the GGC-01 site since the Industrial Revolution, indicated by our modelling, might be partitioned between global warming and local development of subsurface and atmospheric UHIs. Our analysis indicates that the local ground surface temperature was *c.* 8.0°C at the start of the Industrial Revolution and *c.* 8.0°C (Fig. 9) or *c.* 8.4°C (Fig. 10) during the mid-nineteenth century. This analysis requires consideration of the available historical evidence for air and ground surface temperatures from the surrounding region. However, the sources of historical data are distributed over a substantial surrounding area and at different heights, thus requiring correction for lateral variations in climate as well as correction for height.

The UK Meteorological Office (Met Office) has produced representations of historical temperature data, interpolated onto a 1×1 km grid, taking account of location, terrain and height (e.g. Perry and Hollis 2004; Prior and Perry 2014; Hollis *et al.* 2018). However, their analyses do not clearly indicate the factors controlling local variations. We therefore work primarily with the raw data rather than with their gridded versions. The principal present-day weather station in the Glasgow area is at Paisley (Coats Observatory; NS 47955 64092; PWS on Fig. 1; 32 m OD); established in 1883, its data are available from the Met Office (https://www.metoffice.gov.uk/pub/data/weather/uk/climate/stationdata/paisleydata.txt). However, this weather station is *c.* 13 km from the GGC-01 site and post-dates much of the historical record that informed our modelling.

The definition of the International Standard Atmosphere (e.g. Minzner 1977) incorporates a nominal lapse rate, or vertical temperature gradient, of 6.5°C km^{-1}. Lapse rates vary across Britain between *c.* 5 and *c.* 9°C km^{-1}, and at a given site can also vary seasonally and over longer timescales (e.g. Burt and Holden 2010; Holden and Rose 2011). Met Office outputs, such as maps of lateral variations in climate (e.g. Kendon *et al.* 2019), are indicative in central Scotland of a lapse rate of *c.* 8°C km^{-1}, broadly consistent with values across transitions between lowlands and uplands in Scotland and northern England (e.g. Burt and Holden 2010; Holden and Rose 2011), and will be used in this study in lieu of more complex approaches as the resulting corrections across the limited height differences in the Glasgow area are small.

Meteorological data were also recorded from 1856 at Dowanhill weather station (NS 56285 67399; 55 m OD) operated by the University of Glasgow (Roy 1993). This site is in what is now the West End of Glasgow, but was rural before local urban development began in the 1870s. The data series from this weather station was digitized for use in climate syntheses (e.g. Jones and Lister 2004). It was obtained in this form from the University of East Anglia and has been validated for 1857–1920 against contemporaneous records (e.g. General Register Office (Scotland) 1869). Data from a second historical weather station, at the former Belvidere isolation hospital on the eastern outskirts of Glasgow (NS 62400 63400; 16 m OD), which opened in 1877 and closed in 1999 (Richardson 2016), are also available, but have only been validated using local records for 1895–1905 and 1912–15. This weather station was only *c.* 1.5 km from the GGC-01 site, but the brevity of its record limits its usefulness. Finally, the earliest air temperature record in Scotland was compiled for 1764–1896 by Mossman (1896, 1897, 1902) from weather stations in Edinburgh, temperatures being presented for a height of 250 ft or 76 m OD.

These historical temperature records are depicted in Figure 11 and compared in Table 5. Setting aside the effect of lapse rate, the weather stations in Glasgow are mutually consistent and *c.* 0.3°C cooler than Paisley. The comparisons with Edinburgh are not mutually consistent, indicating inter-site variability over different time spans; the Dowanhill–Edinburgh comparison indicates that (excluding the effect of lapse rate) the former site was *c.* 0.2°C warmer than the latter. Including the effect of lapse rate, the best estimates are that



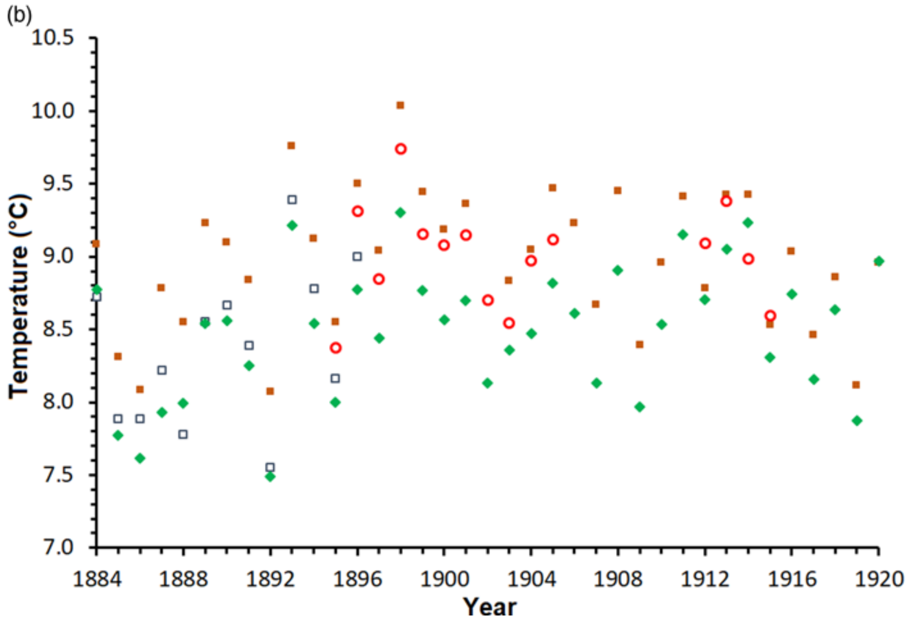


Fig. 11. Annual mean air temperature data for the four weather station datasets discussed in the text: (**a**) for 1764–2019; (**b**) for 1884–1920.

the Belvidere site was *c*. 0.15°C cooler than Paisley and *c*. 0.35°C warmer than Dowanhill.

The Paisley dataset indicates an annual mean temperature during 2002–19 of 9.81°C. Given the aforementioned correction procedure, this would imply 9.96°C at the GGC-01 site in the absence of any UHI. Our modelling (Figs 9 and 10) predicts a present-day annual mean ground surface temperature at this site of 10.7°C. We thus estimate *c*. 0.7°C as the present-day magnitude of the subsurface UHI at the GGC-01 site. Kershaw *et al.* (2010) reported the annual mean UHI in the atmosphere above Glasgow as 1.3°C. The lesser value at Dalmarnock presumably reflects tapering of this UHI away from the city centre.

To the west of Glasgow, borehole temperature measurements were made by Lord Kelvin in 1867 at Blythswood (NS 50030 68230; 2 m OD) and in 1869 at South Balgray (NS

Table 5. *Comparisons of historical temperature records*

Stations	Years	n	D (km)	ΔH (m)	ΔT_M (°C; ±2s)	ΔT_L (°C)
Dowanhill–Belvidere	1895–1915	15	7	39	−0.3601 ± 0.1022	−0.312
Dowanhill–Paisley	1884–1920	37	9	23	0.4816 ± 0.0643	−0.184
Dowanhill–Edinburgh	1857–96	40	*c*. 70	−21	−0.0035 ± 0.0746	0.168
Paisley–Belvidere	1895–1915	15	14	16	0.1524 ± 0.0966	−0.128
Paisley–Edinburgh	1884–96	13	*c*. 80	−44	0.4615 ± 0.0833	0.352

n, number of years of record, allowing for the gap in the record for Belvidere; D, distance between stations; ΔH, difference in height; ΔT_M difference in their annual mean temperatures for the specified years, plus or minus double the standard error in this mean; ΔT_L, difference in temperature that would apply if climate depended entirely on a lapse rate of 8°C km^{-1} with no other effect of position.

55780 67810; 30 m OD) (Thomson *et al.* 1869; Watson *et al.* 2020; Fig. 1). Benfield (1939) estimated the ground surface temperatures at both these boreholes, when measured, as 8.09°C; these values are representative of the contemporaneous air temperature at ground level. For Blythswood, this value indicates (after correction by *c.* −0.06°C for lapse rate and maybe *c.* −0.2°C for location) *c.* 7.8°C at the Belvidere site in 1867. For South Balgray, this value indicates (after correction by *c.* +0.16°C for lapse rate and *c.* 0 for location) *c.* 8.25°C at the Belvidere site in 1869.

During its first decade of operation, in 1884–1893, the Paisley weather station yielded a mean temperature of 8.78°C. The 1.03°C subsequent temperature rise evident at this site is in reasonable agreement with the *c.* 1.2°C estimated by the Met Office (2020) as typical for Scotland on this timescale. Given earlier calculations for lapse rate and horizontal position, the typical air surface temperature at this time at the Belvidere site can be estimated as *c.* 8.6°C. Annual mean air temperature at Dowanhill was 7.92°C in 1867 and 8.56°C in 1869, the mean value during the 1860s being 8.21°C. Proceeding as before, the mean air surface temperature during the 1860s at the Belvidere site might be estimated as *c.* 8.55°C, the values for 1867 and 1869 being *c.* 8.25 and *c.* 8.9°C.

Given the proximity and similar height of the sites, the surface temperature at the GGC-01 site will equal that at Belvidere, plus any UHI effect at the former site. Kelvin's borehole temperature measurements can be seen to be broadly consistent with Figure 9, implying a surface temperature of *c.* 8°C at the GGC-01 site in the 1860s, thus implying no contemporaneous UHI at this site and no climate change since the start of the Industrial Revolution. On the other hand, the Dowanhill temperature dataset indicates a surface temperature of *c.* 8.5°C at the GGC-01 site, broadly consistent with Figure 10, either implying that a modest UHI already existed at this site in the 1860s, or indicating the magnitude of climate change between the late eighteenth century and this time. However, resolving the discrepancy evident between the air temperature and borehole temperature datasets from the 1860s, in favour of either of the model solutions presented, is beyond the scope of the present study.

Our modelling indicates a ground surface temperature of *c.* 8.0°C at Dalmarnock at the start of the Industrial Revolution (Figs 9 and 10). The subsequent net temperature rise of *c.* 2.7°C can be partitioned as *c.* 2.0°C of global warming plus the aforementioned *c.* 0.7°C net subsurface UHI. This estimate of the effect of global warming is broadly consistent with the regional context; for example Westaway and Younger (2016) estimated the effect of global warming since 1880 at Durham in NE England as *c.* 1.7°C, Durham being a small city where no significant UHI is expected (Burt and Horton 2007). Met Office (2020) also estimated *c.* 1.7°C as the typical temperature rise for England since 1884. Mossman's dataset gave mean temperatures of 8.20°C for the 1880s, 8.15°C for the 1860s, and 7.81°C during 1764–73. Using this pattern of variation before the 1880s, the rise in surface air temperature since the Industrial Revolution can be estimated as *c.* 2.1°C at Durham and *c.* 1.6°C at Paisley, for comparison with our *c.* 2.0°C estimate for Glasgow. IPCC (2018) estimate the worldwide mean global warming since the Industrial Revolution as 1.1 ± 0.2°C. As is well known, the effects of global warming increase with latitude from minimal values near the Equator to high values near the poles. The values for Britain (*c.* latitudes 55–56°N) are roughly as expected given this global pattern.

Discussion

We next consider how the 'anthropogenic' geotherms indicated in Figures 9b and 10b for depths of ≤200 m might 'dovetail' at greater depths into 'natural' geotherms, representative of the *c.* 80 mW m^{-2} heat flow characteristic of the study region. Again guided by previous experience (Westaway and Younger 2016) and by preliminary analyses of the study region (Watson *et al.* 2019, 2020), we suggest that at depths greater than *c.* 200 m the geothermal gradient steepens, as a result of upward flow of thermal groundwater, before a conductive geotherm, indicative of *c.* 80 mW m^{-2} of heat flow, resumes. Such a solution, based on Figure 9b, is indicated in Figure 12. The temperature variation within the upward flow has been calculated (after Bredehoeft and Papadopulos 1965; Mansure and Reiter 1979; Lu and Ge 1996) assuming boundaries to this flow at depths of 220 and 320 m and temperatures of 14.6 and 22.2°C, the upper boundary being placed in the sandstone bed just above the Kiltongue coal seam. This flow is modelled with a Péclet number of 0.77 which, for the assumed dimensions and for standard properties of water (density 1000 kg m^{-3}; specific heat capacity 4186 J kg^{-1} °C^{-1}) indicates an upward velocity of 105 mm a^{-1}. We infer that this flow, and most of the heat transported by it, becomes entrained horizontally into a permeable path formed by some combination of naturally permeable sandstone beds within the Scottish Coal Measures Group and former mine workings that became 'permeabilized' by mining. 'Permeabilization' might involve the creation of flow pathways through voids created by 'stoop and room' mine working, where pillars of coal are left *in situ* to support the overburden (as illustrated, for example, by Adams *et al.* 2019, fig. 2), or might instead involve flow through fractures (such as those illustrated in Mills and Holliday 1998, pl. 7), which might form above collapsed

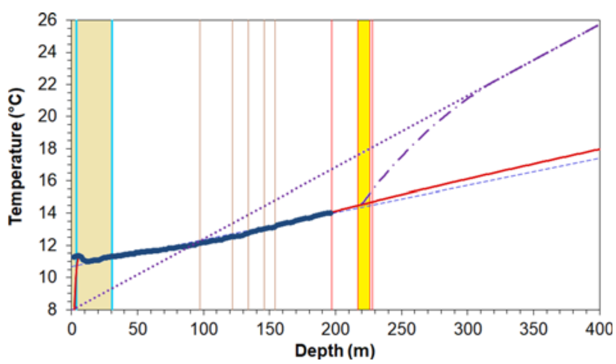


Fig. 12. Extrapolation of Figure 9b to greater depth, with the same display format, to indicate how we envisage the geotherm thus predicted 'dovetails' into a 'natural' geotherm at greater depth. Dot–dash line is the predicted geotherm for depths of greater than 220 m, beyond which we regard the extrapolated geotherm from Figure 9b as no longer applicable. Dotted line is a schematic 'natural' pre-Industrial Revolution geotherm for the area, for 80 mW m^{-2} heat flow with a surface temperature of 8°C. See text for discussion.

workings, including those mined using the longwall method. This suggested pattern of flow might have been anticipated from the analysis by Westaway and Younger (2016) or from the online log of Dalmarnock Colliery (http://scans.bgs.ac.uk/sobi_scans/boreholes/1079959/images/12347725.html), indicating flow of groundwater through sandstone, not to mention the analysis of Hallside by Watson *et al.* (2019). The very low geothermal gradient of only 6 °C km^{-1} in the Hallside borehole was noted by Monaghan *et al.* (2017) but its significance for the subsurface thermal state of the surrounding area was not addressed. Furthermore, given that a major part of the purpose of the GGC-01 borehole was to provide a temperature log, it is unfortunate that this borehole was not drilled sufficiently deep to reveal how the anthropogenically affected part of the geotherm 'dovetails' into the underlying natural geotherm. Part of the issue is that the stratigraphy, including each of the coal seams, was predicted before drilling to be shallower by up to *c.* 10 m than it proved to be (cf. Kearsey *et al.* 2019; Starcher *et al.* 2019). Furthermore, it was already well known that mining occurred in the vicinity to the Kiltongue coal seam, the depth of which can now be estimated as 228 m at this site (Table 3); borehole GGC-01 and the associated temperature log should at least have spanned this depth.

The present modelling (represented by Figs 9–10 and 12) evidently simplifies a complex set of thermal processes. In reality, of course, many aspects will be more complex than has been assumed. For example, annual mean surface temperatures will fluctuate from year to year (as Westaway and Younger 2016, discussed); also, more use will have been made of heating systems in buildings (such as the shelter for homeless people) during cold years than during years characterized by mild winters. As an alternative procedure, one might indeed model the surface heating effect in terms of boundary conditions specified by the downward heat flow at the land surface rather than the surface temperature, as Westaway *et al.* (2015) did. Furthermore (as Westaway and Younger 2016, also discussed), rather than an instantaneous change from a 'natural' to an 'anthropogenic' geotherm (which we have assumed occurred in the year 1771), in reality complex transient thermal behaviour will have occurred, in response to the starts of deep mining and of urban and industrial development in the area. Data that might contribute to modelling of such transient effects, in the late eighteenth and early nineteenth centuries, might include contemporaneous measurements of temperature at depth in mines. Such data exist (e.g. Bald 1819), but we have been unable to find any for the present study area. By keeping the modelling simple we emphasize the main conclusions, the principal one being that the relatively high temperatures in the uppermost *c.* 100 m of the subsurface have been caused by urban development, although we cannot resolve the precise contributions of site-specific v. area development.

One issue concerns the pattern of groundwater flow, which we have assumed to be vertically upward between 320 and 220 m depths. It goes without saying that specifying a different vertical extent would indicate a different vertical Péclet number and rate of vertical flow. Furthermore, the presence of a horizontal component of flow would affect the vertical temperature profile (Mansure and Reiter 1979; Lu and Ge 1996). As a potential constraint on our modelling we therefore looked for information regarding patterns of groundwater flow in the Carboniferous bedrock beneath Glasgow. Ó Dochartaigh *et al.* (2019) reported that little is known about the geometry of this flow (in contrast with other former coalfield regions of Britain, such as County Durham; e.g. Westaway and Younger 2016). They noted that it has been inferred to be directed from the NE, east and SE, citing older references (Robins 1990; Hall *et al.* 1998). However, these works cite other material in turn, but at no point in this chain of referencing does it become clear whether this inference is based on data or simply on the overall form of the landscape where groundwater flow towards the Clyde estuary (Fig. 1) might be expected. We note in passing that Hytiris *et al.* (2016) have reported the temperature of groundwater flowing into one of the tunnels of the Glasgow Subway underground railway at St George's Cross station (at NS 58079 66638; Fig. 1). In this vicinity the Subway is tunnelled into rocks of the Scottish Coal Measures Group (Shipway 1996); the reported water temperature in this locality at <10 m depth varies from *c.* 12 to *c.* 16°C with no clear seasonal pattern. This water is significantly warmer than would be expected given the magnitude of Glasgow's UHI (Kershaw *et al.* 2010), suggesting flow from greater depths; although the geometry of this flow remains unclear, this evidence indicates that at shallow depths some parts of the subsurface beneath Glasgow are significantly warmer than others, and are thus better targets as energy sources. The shallow groundwater flow in the Pleistocene and Holocene sediments beneath the Glasgow area is better understood and has been extensively discussed in relation to the design of the GGERFS (e.g. Ó Dochartaigh 2009; Monaghan *et al.* 2017, 2018). In the Dalmarnock area this water is known to be significantly contaminated. Sources of contamination include Dalmarnock Gas Works (Figs 5 and 6), which released into the subsurface chemicals including cyanides, hydrocarbons, phenols and metallic pollutants (e.g. Envirotreat 2018), and the Shawfield Chemical Works (circa NS 60720 62250, *c.* 500 m ESE of Govan No. 5 Pit in Fig. 2; operational from 1820 to 1968), which generated millions of tonnes of chromite ore processing residue containing soluble (and carcinogenic) chromium-VI ions; until this practice became illegal, this residue was widely used as a landfill material at construction sites in the surrounding area (e.g. Whalley *et al.* 1999; Graham *et al.* 2006; STV 2019). These considerations make the possibility of changes to the pattern of groundwater flow, resulting from GGERFS activities such as well testing and possible future heat production, a significant issue.

A second issue concerns the heat in place at the GGERFS site. The UK mine-water geothermal energy resource is substantial, reported by Adams *et al.* (2019) as 2.2 million GWh. However, previous assessments of mine-water geothermal energy in central Scotland (e.g. PB Power 2004; Ó Dochartaigh 2009; Gillespie *et al.* 2013; Harnmeijer *et al.* 2017) have envisaged exploitation of much deeper mine workings than those in the GGERFS area. For example, PB Power (2004) identified the ten most promising localities in Scotland, all of which involved mine workings at least several hundred metres deep; they estimated the largest individual scheme to have an output of *c.* 17 MW and that the ten schemes in total would output *c.* 83 MW.

However, this study did not address actual temperatures of mine water, it assessed maximum feasible rates of circulation, depending on the size of each set of mine workings and, as Ó Dochartaigh (2009) pointed out, assumed 1 MW of heat output for each 16.75 l s^{-1} of circulation. Using standard theory, this conversion factor is equivalent to assuming that all water being circulated is cooled by 14.3°C, but no evidence was presented that the mine water was warm enough for so much cooling to be plausible, let alone that the water would remain warm enough on a sustainable basis. Gillespie *et al.* (2013) compiled real data for mine-water temperatures and for flow rates that have been sustained by mine pumping in the past (rather than might hypothetically be sustainable in future), but in most cases the two types of data were not from the same mines. The exception was for Polkemmet Colliery (at NS 9190 6278), near Whitburn in West Lothian, for which 549 m deep workings yielded water at 17°C at a flow rate of 75 l s^{-1}. If it is assumed that water from this mine is circulated at this rate and cooled in a future mine-water heating scheme to the *c.* 10°C annual mean surface temperature, the thermal power output would be *c.* 2.2 MW, somewhat below the *c.* 9.5 MW estimated for this mine by PB Power (2004). As Westaway and Younger (2016) have discussed, the lack of credibility of previous claims of potential heat output was one major factor that led to the cancellation of a proposed mine-water-sourced district heating scheme for the Shawfair suburb of Edinburgh, the other major factor being perceived reluctance of potential homeowners to buy property with such an 'unconventional' heat source.

The aforementioned previous mine-water geothermal heat projects in Scotland have envisaged production of water at up to *c.* 22°C from depths of up to *c.* 800 m. The planned design of the GGERFS wells was depicted by Stephenson (2018) and by Adams *et al.* (2019). The well designs as actually drilled are now available from BGS (2020). It is evident from these sources that at each of the principal sites (sites 1, 2 and 3) wells reach the Glasgow Main Coal seam at a depth of *c.* 90 m and the Glasgow Upper Coal seam at *c.* 50 m depth. Although other scenarios might also be envisaged (e.g. Preene and Younger 2014; Loredo *et al.* 2016) a standard design (cf. Verhoeven *et al.* 2014), if these wells are eventually used for heat extraction, would be to produce from the deeper wells and to reinject into the shallower ones, the deeper wells at sites 1 and 3 (GGA-02, BGS ID NS66SWBJ3756, at NS 62324 62869; and GGA-08, BGS ID NS66SWBJ3762, at NS 62248 62751) being 135 m apart. From Figure 9b, the water temperature at the depth of production can be estimated as *c.* 11.6–11.8°C, well below the 16°C threshold below which heat production (using heat pumps) is not considered feasible (Banks *et al.* 2003). Moreover, the preceding analysis indicates that the temperature of the mine water at such shallow depths is primarily a consequence of surface heat propagating downwards, rather than geothermal heat propagating upwards; it is thus arguable that in its proposed configuration the GGERFS should not be classed as a geothermal heat project anyway. Indeed, as Figure 12 indicates, although the combined effect of all anthropogenic temperature changes ΔT (from mining, global warming and Glasgow's UHI) has been to increase the temperature in the shallow subsurface (at depths of <90 m), this combination of effects has reduced the temperature at greater depths (*c.* 90–320 m in Fig. 12). This vertical variation can be illustrated by calculating (after Beltrami *et al.* 2015) the anthropogenic contribution to heat in place between the Earth's surface and depth z, as $(k/\kappa)\int_0^z \Delta T(\zeta)\,d\zeta$, as is done in Figures 9c and 10c. Using this definition, the calculated heat in place reaches a maximum for the depth range of zero to *c.* 90 m, the point at which $\Delta T=0$ in Figure 12. The proposed depth of heat extraction for the GGERFS is close to the depth where the heat in place, thus defined, is at a maximum. In this sense the project design can be considered near-optimal, although this is fortuitous as the coal seams to be utilized were chosen before any subsurface temperature measurements had been made (e.g. Monaghan *et al.* 2018; Stephenson 2018).

Setting aside the question of whether exploitation of such low-temperature heat is feasible, the resource available at the GGERFS is quite small. Detailed calculations depend on the hydrology, which has not yet been determined, but estimates can be made. For example, it might be (optimistically) inferred that this project might cool by 1°C a 1 m thick layer of water extending to *c.* 50 m from each of the production wells. As already noted, two of the *c.* 90 m deep wells that might ultimately be used as production wells are 135 m apart, so the volume of water thus cooled can be estimated as *c.* $2\times\pi\times(50\ \mathrm{m})^2\times1$ m, indicating a mass of *c.* 2×10^7 kg. Using the aforementioned specific heat capacity of water, the heat that might be 'mined' is thus estimated as *c.* 70 GJ or *c.* 20 MWh. If this heat were to be extracted over a single winter season, of duration three months, the time-averaged power output would be *c.* 8 kW; if this heat were to substitute for burning natural gas at a cost of *c.* 3 p per kWh, its value would be *c.* £500, orders-of-magnitude less than the *c.* £9 M cost of the GGERFS project. No calculation of sustainable rates of heat production from the GGERFS is possible at this stage, because the hydrology is unclear; nonetheless our inference that the shallow mine workings at this site are being heated from above, as a result of urban heat losses into the subsurface, rather than through geothermal heat from below, implies that rates of recharge are limited. If connected to appropriate surface infrastructure the GGERFS infrastructure might also be utilized for storage of waste heat (e.g. Adams *et al.* 2019), maybe on a seasonal timescale, potentially increasing its value as part of an integrated heat network. In connection with this possibility, we note that the River Clyde at the site is itself a significant source of heat. The mean flow rate can be taken as 47.72 $m^3\ s^{-1}$, at the Daldowie gauging station (at NS 672 616, *c.* 10 km upstream of the present study area; DGS on Fig. 1), as reported by Marsh and Hannaford (2008). At Glasgow Green, between Dalmarnock and Glasgow City Centre, the water temperature in the Clyde is typically *c.* 10°C, fluctuating between *c.* 16°C in summer and *c.* 4°C in winter (Burt *et al.* 2017). If all this flow could be cooled by 1°C, the thermal power output would be *c.* 200 MW; this potentially significant output might be developed as a more effective local option for heat supply than the GGERFS, although the GGERFS might itself be adapted to store surplus heat extracted from the Clyde.

Finally, as part of our analysis we have established the manner in which surface warming in the Glasgow area has been partitioned between global warming and UHI development. Our efforts thus increase to three the inventory of British cities for which this has been determined, following Cardiff (Patton *et al.* 2015, 2019) and Newcastle upon Tyne (Westaway and Younger 2016). Similar effects have also been recognized in other cities, such as Zürich, Switzerland (Bayer *et al.* 2016). Our analysis of this effect for Glasgow was greatly facilitated by the availability of borehole temperature records from the 1860s, as part of Lord Kelvin's research legacy (Thomson *et al.* 1869). Knowledge of UHI effects in cities is important for devising strategies for mitigation of future high urban temperatures. Nonetheless, for the case of Glasgow (like Newcastle upon Tyne; Westaway and Younger 2016) it is currently unclear whether the subsurface UHI is maintaining the atmospheric UHI or vice versa, or, indeed, what feedbacks exist between the two. Nonetheless, case studies such as this, where local UHI effects and effects of global warming can be distinguished, are important for establishing the reality of both types of effect. The existence of UHIs, or temperature rises caused by land-use changes around expanding urban areas, was accepted (e.g. Dronia 1967) before the concept of anthropogenic global warming was recognized. Some more recent studies of borehole temperature records have indeed recognized UHI effects but no systematic effect of climate change (e.g. Hale *et al.* 2006). Such information is sometimes cited by climate change deniers as evidence that anthropogenic global warming is 'fake news'. Case studies such as the present analysis contribute to the overwhelming weight of evidence to the contrary.

Conclusions

We have modelled the 197 m subsurface temperature record from borehole GGC-01 at the GGERFS site in Dalmarnock in the east of Glasgow. This record is significantly perturbed away from its natural state, in part because of the 'permeabilizing' effect of past nearby coal mining and in part due to surface warming caused by the combination of anthropogenic climate change and creation of a subsurface urban heat island as a result of local urban development. We estimate the total surface warming effect as 2.7°C, partitioned as 2.0°C of global warming since the Industrial Revolution and 0.7°C of local UHI development. We cannot resolve the precise combination of local factors that influence the surface warming, because uncertainty in the subsurface thermal properties trades against uncertainty in the history of surface warming (Figs 9 and 10). However, the background upward heat flow through the shallow subsurface in this area is estimated as only *c.* 28 to *c.* 33 mW m^{-2}, depending on choice of other model parameters, well below the *c.* 80 mW m^{-2} expected in the Glasgow area. We infer that the 'missing' geothermal heat flux is entrained by horizontal flow at depth beyond the reach of the shallow GGC-01 borehole.

Although the shallow subsurface in the study area is warmer than it would have been before the Industrial Revolution, at greater depths – between *c.* 90 and >300 m – it is colder, due to the reduced background heat flow. In future the GGERFS project may utilize water from depths of up to *c.* 90 m, but the temperature of this water is maintained largely by the past effect of surface warming, caused by climate change and urban development; it is thus a resource that might be 'mined' but not sustainably replenished and, being the result of surface warming rather than upward heat flow, arguably should not count as 'geothermal' heat in the first place. Our analysis thus indicates that the GGERFS site is a poor choice as a test site for mine-water geothermal heat.

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Author contributions **RW**: conceptualization (lead), data curation (supporting), investigation (supporting), methodology (lead), software (lead), supervision (lead), visualization (lead), writing – original draft (lead), writing – review & editing (equal); **SMW**: data curation (lead), investigation (lead), writing – review & editing (equal)

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Correction notice: The supplementary material link has been updated.

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