Revaluating Glasgow's Heat Flow Dataset to Account for Corrections for Palaeoclimate: a Case Study of the Maryhill Borehole

Sean M. Watson*, Rob Westaway and Neil Burnside

James Watt School of Engineering, University of Glasgow, James Watt (South) Building, Glasgow G12 8QQ, UK

*s.watson.3@research.gla.ac.uk

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ABSTRACT

Hot sedimentary aquifers represent a substantial low-carbon heating resource in the UK. 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. Recent 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. 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. The objective of this work is to unravel the effect of palaeoclimate on existing geothermal data in the vicinity of Glasgow, one of Britain's largest cities, revealing an estimation of the true geothermal potential in this city and, indeed, throughout the western Midland Valley of Scotland. Past workers have determined heat flow of 60 mW m^{-2} in the Glasgow area. This has been based on 4 boreholes; Blythswood, South Balgray, Hurlet and Maryhill. Applying a correction for palaeoclimate to the Maryhill borehole dataset, the estimated heat flow increases to c. 80 mW m^{-2}. The base of the hot sedimentary aquifer resource is estimated at c. 2-2.5 km depth beneath Glasgow; extrapolating the corrected geothermal gradient gives a temperature of c. 80 °C, significantly greater than previously thought, at this depth. The preliminary results of this analysis are highly encouraging: if heat at this temperature can be extracted then it may prove significant for decarbonisation of heat supply and alleviation of fuel poverty in Glasgow, and indeed for other areas of the UK.

1. INTRODUCTION

The catalyst for geothermal exploration worldwide is the need to produce low carbon renewable energy (e.g. Younger, 2015). As a consequence of the global oil crisis in the 1970's, geothermal resources in Britain were assessed as a potential alternative for electricity generation and heat supply. The hot sedimentary aquifer setting 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 and Gray, 1986; Brereton et al., 1988). Despite concluding that a likely exploitable temperature of 60 °C could be accessed at c. 2 km depth, the drilling risks and associated expenditure meant that the resource remained untapped.

In Scotland, heat accounts for 51% of energy demand (Scottish Government, 2018). The Scottish Government has set a target of producing 11% of heat demand from renewable sources by 2020. In 2017, 5.9% of heat demand in Scotland was met from renewable resources (Scottish Government, 2019). Furthermore, in 2016, 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 space heating is achieved through the burning of natural gas (Dukes, 2018). Geothermal energy represents an, as yet unused, supply 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 hot sedimentary aquifers within Kinnesswood Formation and Knox Pulpit Formation sandstones (Browne et al. 1985; 1987; Gillespie et al. 2013). The areas of the MVS where the resource is present encompasses the largest cities in Scotland, Glasgow and Edinburgh. The urban development in the MVS has been a legacy of economic development, mainly fueled 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, research has been conducted on behalf of the Scottish Government to investigate the potential geothermal resource in Scotland (e.g. Gillespie et al., 2013). Most recently, in the Clyde Gateway Regeneration area of the east end of Glasgow, drilling of observational and monitoring boreholes has commenced at the Glasgow Geothermal Energy Research Field Site (GGERFS). This site is part of the Natural Environment Research Council (NERC) funded UK Geo-energy Observatory (UKGEOS) project. The objective of the GGERFS is to investigate the geothermal potential of the flooded, abandoned mine workings beneath this area of the city (Monaghan et al., 2017). Despite the long tradition of coal exploration, and minor oil and gas exploration in the MVS, there is a scarcity of deep onshore boreholes in central Scotland. The hydraulic properties of both the flooded abandoned mine-workings and the deeper hot sedimentary aquifer remain poorly understood (Ó Dochartaigh et al., 2018), and uncertainty still remains regarding the likely temperature accessible in either potential geothermal resource setting however recent efforts have begun to investigate this (Watson et al., in review). Applying corrections for the effect of palaeoclimate on heat flow measurements would be a significant step forward in increasing the understanding of subsurface temperatures and potential geothermal resource in Scotland.

The aforementioned previous studies of the potential geothermal resource in the UK neglected, or underplayed, corrections to heat flow measurements for the cooling effects from periods of lower temperatures during the Pleistocene. That past climate change can perturb subsurface temperature gradients, from which heat flow is calculated, in boreholes of several hundred metres depth was established decades ago (e.g. Benfield, 1939; Anderson, 1940; Jessop, 1971; Beck, 1977). 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. Recent work on correcting measurements in boreholes across the UK, accounting for warming since the last glaciation, resulted in a positive correction to heat flow. Westaway and Younger (2013) suggested that this correction is of the order of c. 20 mW m^{-2}. This would indicate that a lack of consideration of palaeoclimate has resulted in an underestimate of heat flow, and therefore, geothermal potential across the UK (Westaway and Younger, 2013; Busby et al., 2015; Westaway and Younger, 2016). The corrected heat flow measurements combined with the focus on renewable heat generation, mean that geothermal exploration and production would be at much shallower depths than previously considered. This has the effect of significantly reducing drilling costs and risk, lowering the significant economic barriers to the first steps of geothermal development. The objective of this paper is to unravel the effect of palaeoclimate for existing geothermal data from Glasgow.

2. GEOLOGICAL SETTING

Underlying the central belt of Scotland is the MVS, a WSW–ENE-oriented graben of Carboniferous age. The basin is bounded to the north by the Highland Boundary Fault and in the south by the Southern Upland Fault. It contains an internally complex arrangement of several Upper Palaeozoic sedimentary basins and small inliers of Lower Palaeozoic metamorphic rocks (Cameron and Stephenson, 1985; Trewin et al., 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 extensive urban development, are located. To the north, the topography rises to the dominant landscape features of the area, the Campsie Fells, Kilpatrick Hills and Gargunnock Hills (Fig. 1). To the south, the Beith-Barrhead Hills and Cathkin Braes form analogous high topography, each of these upland areas being in the footwalls of major normal faults of Carboniferous age. The lower ground between these major faults is largely underlain by Carboniferous sedimentary and igneous rocks transected by a complex network of lesser faults (Forsyth et al. 1996; Hall et al. 1998). This bedrock geology is dominated by cyclic successions of sedimentary rocks, namely the Scottish Coal Measures Group and the Clackmannan Group. 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 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 of the city is formed by these erosion resistant lava flows, which crop out in fault bounded blocks within the sedimentary sequence. Stratigraphically below the lavas, the oldest lithologies in the area range in age from Devonian to Lower Carboniferous and crop out to the north west of the Kilpatrick Hills and Campsie Fells. 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). 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).
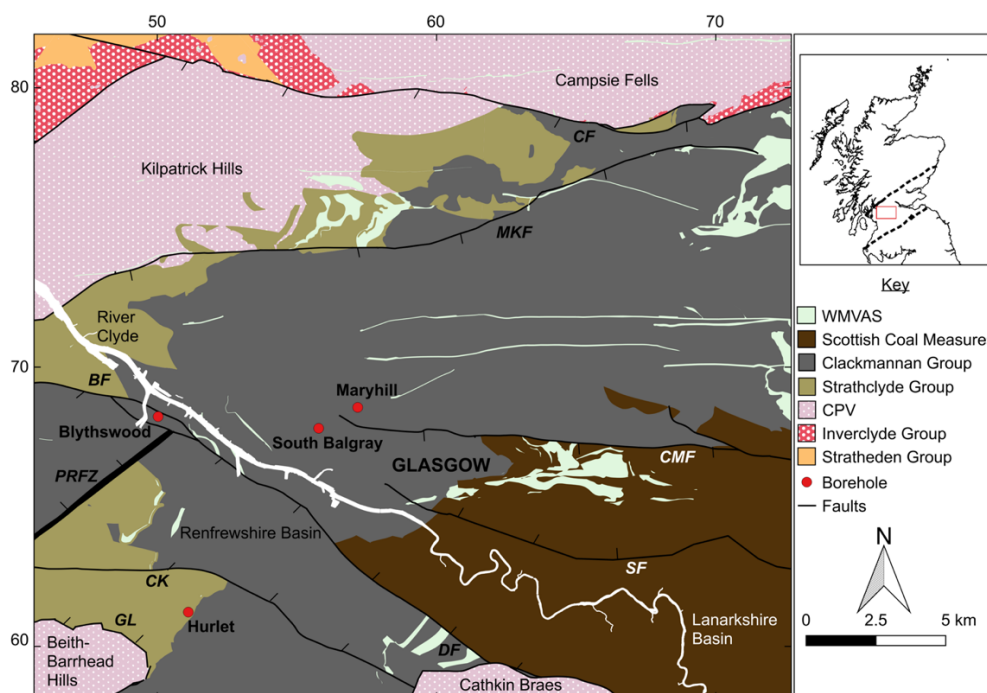

Figure 1: Simplified solid geology, structure and locations of studied boreholes in Glasgow and the surrounding conurbation, with inset showing location within the Midland Valley of Scotland. Stratigraphic units depicted here include: CPV, Clyde Plateau Volcanic Formation of the Strathclyde Group; and 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, Glennifer Fault; MKF, Milngavie-Kilsyth Fault; PRFZ, Paisley Ruck Fault Zone; and SF, Shettleston Fault. The co-ordinates (north and east) are in kilometres within British National Grid 100 km quadrangle NS.

3. PALAEOCLIMATE CORRECTIONS AND BOREHOLE GEOTHERMAL DATA

There is a renewed interest in the UK's potential geothermal resources. The reason for this can be attributed to two developments: (1) a focus on renewable heat generation and resulting re-assessment of the lower temperature resource; and (2) a rigorous re-assessment of UK heat flow data to account for the effects of palaeoclimate and topography. Research undertaken 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 believed (Westaway and Younger 2013, 2016; Busby et al., 2015).

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 geothermal gradient at any site is a function of the local heat flow and conductivity, 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 geothermal gradient measurements taken from a variety of boreholes.

Raw heat flow measurements typically require correction for palaeoclimate if temperatures are to be reliably extrapolated to depths greater than those where temperature is measured. These corrections are an essential step in quantifying the geothermal resource and have not been considered appropriately in assessments of the UK geothermal dataset (Westaway and Younger, 2013). For almost all boreholes, the correction due to palaeoclimate results in a higher heat flow than the initial raw measurement.

The average temperature gradient for boreholes in the MVS is reported as 22.5 °C km^{-1} (Browne et al. 1987). A region of relatively high heat flow has been reported in the west of the Midland Valley, including the Greater Glasgow area, of 60 mW m^{-2} (Browne et al. 1987; Busby et al. 2011). This has been tentatively attributed to east-west crustal thinning, a more highly 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). This heat flow determination for the Glasgow area is based upon data from four boreholes; Blythswood, South Balgray, Hurlet and Maryhill (Table 1; Fig. 2).

These borehole datasets may be particularly sensitive to the effects of palaeoclimate. The location of Britain, at a range of latitude with a temperate climate at present but where arctic conditions prevailed for most of the Pleistocene, means that the palaeoclimate correction, for a borehole of a given depth, is particularly large. Furthermore, as most UK heat flow measurements to date have been taken from shallow boreholes, the magnitudes of the required corrections are significantly increased (Westaway and Younger, 2013).

Table 1. Borehole data

Name	NGR	Date[1]	Height[2] (m)	Z[3] (m)	Z1[4] (m)	Z2[4] (m)	T (°C)	Q (mWm^{-2})	Ref[6]
Blythswood	NS 50030 68230	1868.01	2	117.4	18	105	12	52	A,B
South Balgray	NS 55780 67810	1869.07.13	30	320.61	0	137	15.3	64	A,B
Hurlet	NS 51110 61230	1979.5.18	30.31	304.3	95	295	-	60	B, C
Maryhill	NS 57178 68558	1983.12.18	40	306.5	100	303	20.03	63	B, C

(1) Date corresponds to date of last temperature measurement. If not stated, then taken as the same as the date that drilling concluded. (2) Height (m) above sea level taken from borehole log. (3) Z is depth of well bottom taken from borehole log. (4) Z1 to Z2 is the depth range over which BGS have measured heat flow Q. For boreholes where Q not measured, Z2 also corresponds to depth of deepest temperature measurement. (5) Type of measurement. EQM: equilibrium measurement; BHT: bottom hole temperature measurement; LOG: log temperature; DST: drill stem test. (6) References denote: A: BGS borehole log; A: Thomson et al. (1869); B: Burley et al. (1984); C: Busby (2019).
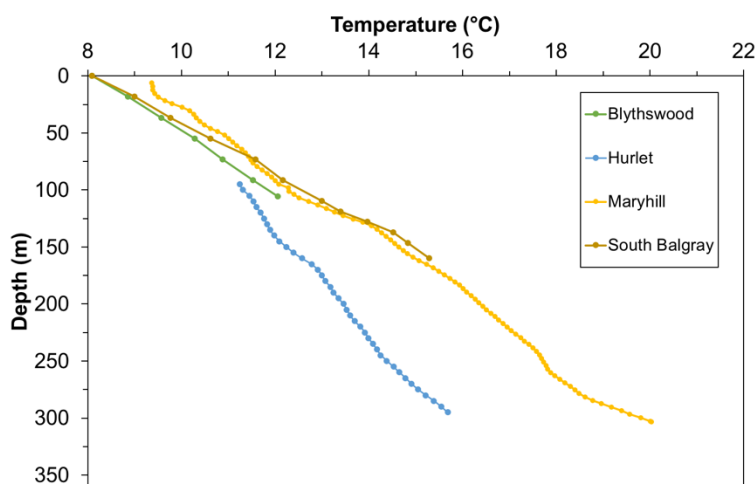

Figure 2: Borehole temperature measurements for the four boreholes included in this study. Data summarized in Table 1.

The Blythswood and South Balgray boreholes were drilled in the 1860's in order to prospect for coal and ironstone, minerals which were extensively mined in this area through the 19th and 20th century (Watson et al., in review). As for Maryhill, each of these boreholes were drilled through a sequence of the Limestone Coal Formation. The Hurlet borehole was drilled in 1978 to investigate the stratigraphy of the Lower Carboniferous in the MVS, including the Lawmuir Formation and the underlying CPV (IGS, 1980). The lower geothermal gradient evident in this borehole (Fig. 2) reflects the higher thermal conductivity of these rocks. A summary stratigraphic column for each of the boreholes is displayed in Fig. 3.

The most comprehensive of these four datasets is that from the Maryhill borehole, drilled in north-west Glasgow (Fig. 1). The Maryhill borehole was drilled by the British Geological Survey (BGS) as a first step towards assessing the geothermal resource within Glasgow (Wheildon et al. 1985). The borehole was sited to give a 300 m sequence of rock, free of old 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). 99 measurements of temperature were made from 100 - 303 m depth, together with 82 thermal conductivity measurements on core (Browne et al. 1987). This borehole dataset was assessed by Watson et al. (in review) and determined to be a robust and reliable dataset representative of the undisturbed thermal state beneath Glasgow. It is for this reason that it shall be used for this preliminary assessment on the effect of palaeoclimate on heat flow in Glasgow.
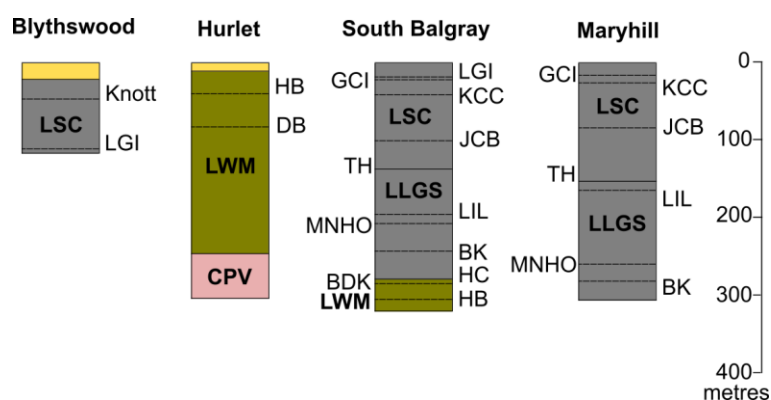

Figure 3: Borehole stratigraphy. Arranged west to east (left to right) across study area. Taken from ground level at each site and not correlated stratigraphically. Abbreviations of stratigraphic units: LSC, Limestone Coal Formation; LLGS, Lower Limestone Group Formation; LWM, Lawmuir Formation; CPV, Clyde Plateau Volcanic Formation. Abbreviations of coal and ironstone seams and limestone bands: Knott, Knott Coal; LGI, Lower Garscadden Ironstone; GCI, Garibaldi Clayband Ironstone; KCC, Kilsyth Coking Coal; JCB, Johnstone Clayband Ironstone; TH, Top Hosie Limestone; LIL, Lillie's Shale Coal; MNHO, Main Hosie Limestone; BK, Blackhall Limestone; HC, Hurlet Coal; BDK, Baldernock Limestone; HB, Hollybush Limestone; DB, Dykebar Limestone. Yellow shading used to denote Quaternary deposits. Data from: IGS (1980), Monro (1983), and the BGS online borehole viewer.

3. RECONSTRUCTING A PALAEOTEMPERATURE HISTORY FOR WESTERN SCOTLAND

The magnitude of the palaeoclimate correction depends on the assumptions about palaeotemperature anomalies and their durations. Despite air temperatures during Pleistocene cold stages decreasing northward, in much of northern Britain the Earth's surface was not exposed to these low temperatures for part of the Late Pleistocene due to the insulating effect of cover by ice sheets. Therefore, detailed correction for each locality studied depends on the local histories of air temperature anomalies and of ice cover (Westaway and Younger, 2013).

The ability to resolve the effect of palaeoclimate on heat flow has been made easier by the abundance of information now available on Quaternary climate history. As discussed in Westaway and Younger (2013), the development of this field of research over past decades allows palaeoclimate corrections to heat flow to be calculated with significantly greater confidence than was previously possible. The arctic climatic conditions prevalent in Britain during much of the last climate cycle can be determined from a variety of data sources. These include, marine and sedimentary terrestrial records and ice cores, as well as numerical simulations of climate change. Palaeotemperatures can be reconstructed from proxy data from these aforementioned sources. Despite the associated uncertainties with each data source, the use of multi-proxy data can provide reasonably robust reconstructions of palaeotemperature. This approach of using a variety of data sources to verify predictions of changes in surface air palaeotemperature shall be adopted within this present study of applying corrections for palaeoclimate to heat flow in the Maryhill borehole.

From assessment of the literature on the glacial chronology of the Scottish Ice Sheet (SIS) and British and Irish Ice Sheet (BIIS), it is noted that various authors have incorporated data from the North Greenland Ice Core Project (NGRIP) into modelling the timing and dynamics of SIS/BIIS events, modelling of deglaciation of the SIS/BIIS, and for comparison with evidence of palaeotemperatures across Britain (e.g. Hubbard et al., 2009; Brooks et al., 2012; Ballantyne and Small, 2018). The ice sheets of Antarctica and Greenland represent continuous stratigraphic sequences of frozen atmospheric water vapour. Temperature-controlled fractionation between the light isotope of oxygen (^{16}O) and the heaver isotope (^{18}O), during precipitation over the ice sheet, enables variation of the $^{16}O/^{18}O$ ratio of ice to be used as a proxy for palaeotemperature. The alternating pattern of stadials and interstadials is reflected in many different palaeoclimatic records, however it is particularly visible within the Greenland Ice Core records, due to their very high stratigraphic and temporal resolution and precise dating (Rasmussen et al., 2014).

This study utilizes NGRIP oxygen isotope data (NGRIP $\delta^{18}O$) to model past changes in land surface air temperature in western Scotland. To calibrate the NGRIP $\delta^{18}O$ data, this work includes multi-proxy data of mean annual air temperature from sites across Scotland and Britain, similar in approach to Westaway and Younger (2013). By approximating the NGRIP temperature as a series of step functions the modelling of the palaeoclimate can be completed. This history of surface temperature variation (Fig. 4) shall be applied to the Maryhill borehole.
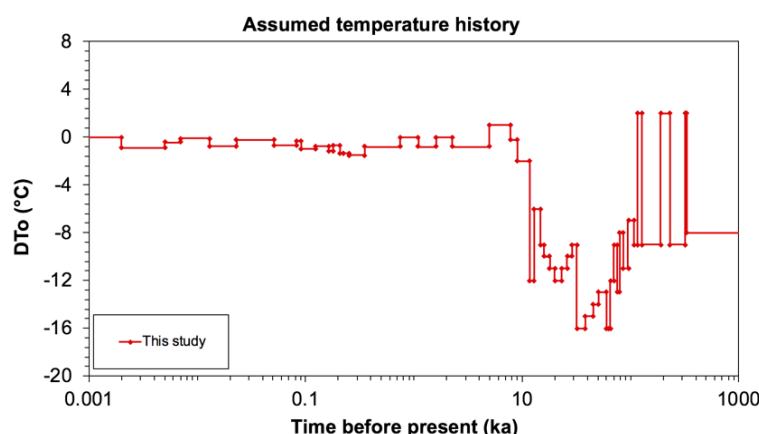

Figure 4 Assumed temperature history for the Maryhill borehole. Based upon surface air temperature fluctuations observed from the NGRIP dataset and studied palaeotemperature observations in Scotland and UK. Follows methodology and assumptions made within Westaway and Younger (2013). Note the logarithmic time scale.

The temperature fluctuation within years immediately prior to subsurface temperature measurements being made in a borehole have a disproportionate effect on the required correction (Westaway and Younger, 2013; Westaway and Younger, 2016). It was therefore necessary to compile a continuous record of annual mean surface air temperature across the timescale of recent centuries to the present day (Fig. 5). The longest continuous records of temperature in Scotland were developed by Mossman (1896, 1897, 1902) and were gathered from meteorological registers kept in Edinburgh during 1731-1736 and 1764-1896. In the west of Scotland, the weather station with the most extensive dataset in the Glasgow area is that at Paisley, named the Coats Observatory (at NS 47395 64223). This observatory was built in 1883 and has provided a continuous meteorological record from 1884 to the present day. The overlap between each dataset offered the opportunity to create a continuous record from 1764 to the present day, accounting for the regional differences in temperature between the east coast and west coast of Scotland.
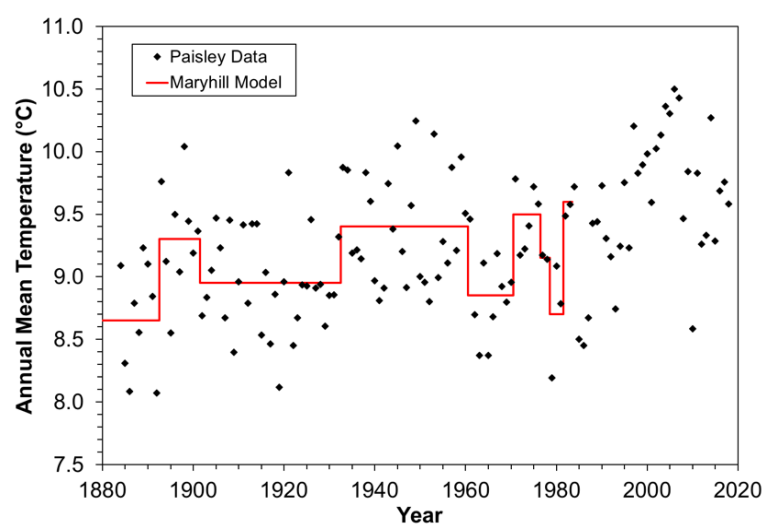

Figure 5: Sequence of annual mean surface temperature measurements at the Paisley Meteorological Station, approximated as a series of step functions to facilitate modelling of the temperature history for the Maryhill borehole.

4. PALAEOCLIMATE CORRECTION TO HEAT FLOW ANALYSIS

Using the same theory and modelling approach as in Westaway and Younger (2013, 2016), a palaeoclimate correction to heat flow for the Maryhill borehole was calculated. As an input to the modelling software, accounting for the percentage of each lithology

present in the borehole, the harmonic mean thermal conductivity and thermal diffusivity were determined across the depth range within the borehole over which the raw heat flow was calculated. Mean values of thermal conductivity for each lithology in the borehole were determined either from BGS thermal conductivity measurements in the borehole or from the literature. Similarly, appropriate values of density and specific heat capacity for each lithology were obtained from the literature, and values of thermal diffusivity then calculated. The thermal properties applied to lithologies and the percentage of lithologies within the Maryhill borehole shown in Tables 2 and 3. This analysis results in harmonic means of 1.79 W m^{-1} K^{-1} for thermal conductivity and 0.809 mm^2 s^{-1} for thermal diffusivity of across the depth range over which heat flow was determined in the borehole.

Table 2. Thermal Properties Applied to Maryhill Borehole Lithologies

Property	OH	Coal	Ist	Lst	Mdst	Slst	Sst	Strk	Dolr	Tesc	WT
k (W m^{-1} K^{-1})	0.59	0.40	2.85	2.85	1.41	1.84	4.54	2.42	1.81	2.16	2.00
c (J kg^{-1} K^{-1})	4185	1300	880	880	770	910	930	860	858	858	858
ρ (kg m^{-3})	1000	1350	2760	2760	2600	2680	2460	2680	2870	2870	2870
κ (mm^2 s^{-1})	0.141	0.228	1.173	1.173	0.704	0.754	1.984	1.050	0.735	0.877	0.812

Abbreviations: OH, Open Hole; IST, Ironstone; Lst, Limestone; Mdst, Mudstone; Slst, Siltstone; Sst, Sandstone; Strk, Seatrock; Dolr, Dolerite; Tesc, Teschenite; WT, 'White Trap' (i.e., weathered dolerite).

Table 3. Percentage of Lithologies in Maryhill Borehole Log

	OH	Coal	Ist	Lst	Mdst	Slst	Sst	Strk	Dolr	Tesc	WT
∑ Thickness (0-306.5) (m)	2.34	1.34	1.51	1.92	119.03	33.34	63.56	2.65	13.42	53.35	14.04
% (0-306.5)	0.76	0.44	0.49	0.63	38.84	10.88	20.74	0.86	4.38	17.41	4.58
∑ Thickness (100-303.5) (m)	0.00	0.58	0.19	1.92	77.03	23.58	18.89	0.00	13.42	53.35	14.04
% (100-303.5)	0.00	0.29	0.09	0.95	37.95	11.62	9.31	0.00	6.61	26.28	6.92

This is the total thickness of each lithology in the Maryhill borehole log, calculated in metres (m) and as a percentage (%). These results are used to determine the harmonic mean thermal conductivity and harmonic mean thermal conductivity across the entire borehole and the depth range over which the raw heat flow was determine. Abbreviations: OH, Open Hole; IST, Ironstone; Lst, Limestone; Mdst, Mudstone, Slst, Siltstone; Sst, Sandstone; Strk, Seatrock; Dolr, Dolerite; Tesc, Teschenite; WT, 'White Trap' (i.e., weathered dolerite).
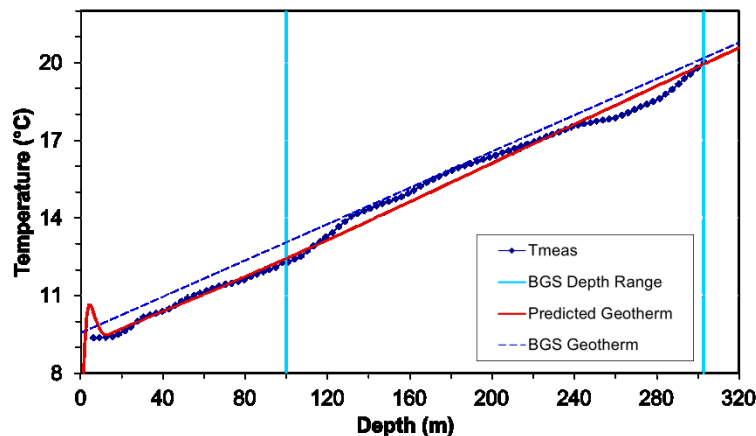

Figure 6: Maryhill borehole geothermal gradient matched with this study's predicted geothermal gradient accounting for the palaeoclimate correction.

The annual mean surface temperature for 1983, measured at the Paisley Coats Observatory and accounting for lapse rate, given the difference in height, was 9.55 °C at the site of the Maryhill borehole. Based upon the modelling software of Westaway and Younger (2013, 2016), a palaeoclimate corrected geotherm has been obtained for the Maryhill borehole. This is matched to the raw, uncorrected, temperature observations (Tmeas) made within the borehole (Fig. 6). Perturbations of the raw temperature observations, like those from c.120-200 m and c. 240-300 m can be explained by the higher percentage of particular lithologies, with related thermal conductivity, over a particular depth range, as displayed in Table 3.

As shown in Table 1, the uncorrected heat flow for the Maryhill borehole is 63 mW m^{-2}. The above analysis indicates that the corrected heat flow, accounting for the effect of palaeoclimate, is 80 mW m^{-2}. Using the harmonic mean thermal conductivity, the uncorrected and corrected geothermal gradients are 35 and 44.5 °C km^{-1}.

The corrected geothermal gradient can be extrapolated to depth to provide a preliminary estimate of the temperature in the potential hot sedimentary aquifer beneath Glasgow, using the harmonic mean thermal conductivity and thermal diffusivity of the Lower Carboniferous and Upper Devonian stratigraphy between the base of the Maryhill borehole and the hot sedimentary aquifer (Fig. 7). The depth to the base of the Upper Devonian aquifer at the site is estimated to be 1880 m. The harmonic mean thermal conductivity and thermal diffusivity of the stratigraphy between the base of the borehole and the base of the Upper Devonian is determined to be 2.55 W m^{-1} °C^{-1} and 1.085 mm^2 s^{-1}. Assuming a surface temperature of 9.55 °C, the corrected geothermal gradient is extrapolated to give a temperature at 1880 m is c. 83 °C with a geothermal gradient of 38.94 °C km^{-1}.
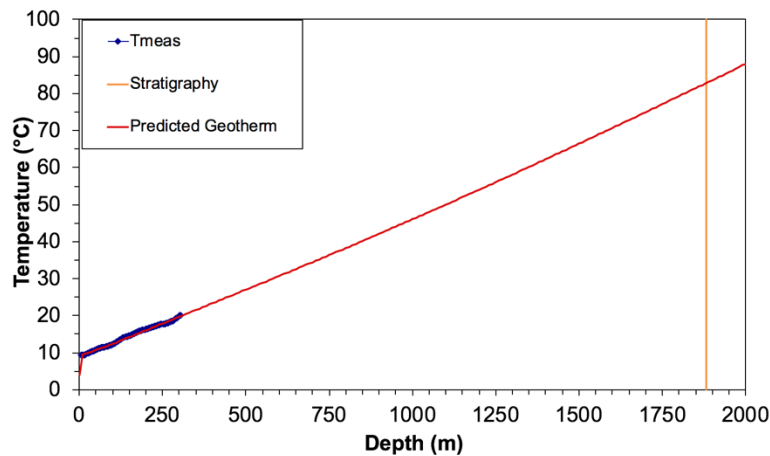

Figure 7: Maryhill borehole geothermal gradient matched with this study's predicted geothermal gradient accounting for the palaeoclimate correction. Corrected geothermal gradient extrapolated to the base of the Upper Devonian Stockiemuir Sandstone Formation at c. 1880 m depth.

5. IMPLICATIONS FOR ASSESSING THE GEOTHERMAL ENERGY POTENTIAL OF GLASGOW

The present study is timely given the recent development of the Glasgow Geothermal Energy Research Field Site (GGERFS). This site is part of the Natural Environment Research Council (NERC) funded UK Geo-Energy Observatory (UKGEOS) project. The objective of the GGERFS is to investigate the geothermal potential of the flooded, abandoned mine workings beneath this area of the city (Monaghan et al., 2017); however, there may be an opportunity in the future for the scope of the project to be extended to investigate the hot sedimentary aquifer setting beneath Glasgow. By assessing the existing heat flow and temperature data in Glasgow and applying the necessary corrections to account for the effect of palaeoclimate, this present study has offered the first insight regarding the "true" heat flow and a more representative estimate of the likely temperature in the potential hot sedimentary aquifer resource beneath Glasgow. The preliminary results of this analysis are highly encouraging: heat at this temperature may prove significant for decarbonisation of heat supply and alleviation of fuel poverty in Glasgow, and indeed for other areas of the UK. It would also allow for the possibility that higher temperature resources can be reached at shallower depths, reducing drilling risk and associated costs for an exploratory geothermal drilling project. The approach taken within this present study is therefore essential when seeking to determine the potential geothermal resource in Scotland and more broadly across the UK.

6. CONCLUSION

Hot sedimentary aquifers represent a substantial low-carbon heating resource in the UK. Previous studies of the geothermal potential of the UK neglected to correct heat flow measurements for the cooling effects from periods of lower temperatures during the Pleistocene. This effect is 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. The objective of this work has been to unravel the effect of palaeoclimate on existing geothermal data in the Glasgow area, revealing an estimation of its true geothermal potential. Applying a correction for palaeoclimate to the Maryhill borehole dataset increases the estimated heat flow from 63 to c. 80 mW m^{-2}. The base of the hot sedimentary aquifer resource is estimated at c. 2-2.5 km depth beneath Glasgow; extrapolating the corrected geothermal gradient gives a temperature of c. 80 °C, significantly greater than previously thought, at this depth. The preliminary results of this analysis are highly encouraging: if heat at this temperature can be extracted then it may prove significant for decarbonisation of heat supply and alleviation of fuel poverty in Glasgow, and indeed for other areas of the UK.

7. ACKNOWLEDGMENTS

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