OR/17/006 Geothermal data for the Glasgow area

Geothermal energy is the heat that is generated and stored within the Earth. If it can be extracted, this heat can be used as an energy source. Heat flow is the standard means of gauging the size of the heat resource beneath any given point at the Earth’s surface. This is the measure of the amount of heat travelling through Earth’s crust, generally expressed in milliwatts per metre square (mW m\(^{-2}\)). Heat flow can be calculated using borehole measurements of the geothermal gradient (the rate at which temperature increases with depth) and the thermal conductivity of the rock (e.g. see Gillespie et al., 2013[1]). Thermal conductivity can be more difficult to measure than temperature, particularly in heterolithic strata, and is therefore not always available in conjunction with temperature measurements. Temperature data measured in boreholes provide the best currently available alternative to heat flow measurements as a means of examining the size and distribution of the heat resource beneath Scotland (Gillespie et al., 2013[1]). Heat flow, thermal conductivity and temperatures are considered as thermal data. Thermal data for Glasgow and the Clyde Gateway are summarised below and discussed in terms of minewater geothermal and Hot Sedimentary Aquifer (HSA) geothermal.

Heat flow

The most recent heat flow map for the UK is shown in Figure 47, from Busby (2011)[2]. This heat flow map originates from the third version of the Geothermal Catalogue of the UK (Rollin, 1987[3]) and includes data from 390 deep (>1000 m) boreholes.
Scotland sits on a geologically stable part of Earth’s crust and there is no indication of the presence of a substantial heat resource in accessible parts of the subsurface (Gillespie et al., 2013). However, it is thought that the size of the heat resource may have been underestimated due to the impacts of palaeoclimate, as discussed below (e.g. Westaway and Younger, 2013; Busby et al., 2015).

The heat flow dataset for Scotland is relatively small, and no new values have been reported since the 1980s (Gillespie et al., 2013). In the most recent report on the potential for deep geothermal energy in Scotland, Gillespie et al. (2013) compiled heat flow values from 35 onshore boreholes in Scotland (listed in Table 3). Thirty-four of these data are collated in the second version of the Catalogue of Geothermal Data for the UK (Burley et al., 1984). Data for the Glenrothes borehole came from Brereton et al. (1988).

Most of the reported heat flow values in Scotland derive from measurements in boreholes <400 metres deep (Gillespie et al., 2013). Because geothermal temperatures from a depth of less than c.2 km depth, were impacted by cooler surface temperatures in previous glaciations in comparison to today’s surface temperatures, temperature measurements from shallow depths in the UK generally underestimate the geothermal gradient (e.g. Westaway and Younger, 2013, discussed below). In addition, since thermal conductivity measurements are representative of the rock between the location of temperature measurements in a particular borehole, the greater this distance is, the greater the thickness of the crust being accounted for. Therefore, heat flow calculated from temperature measurements at greater depths are often considered to be more reliable (Gillespie et al., 2013). The following comments are summarised from Gillespie et al. (2013) and reflect the degree to which heat flow measurements in Scotland can be considered

Figure 47  Heat flow map for the UK (note 1) version from Busby (2011).
accurately to reflect the size of the heat resource at depth:

- Nine values are from lake sediments in Loch Ness; published values include significant corrections so their reliability, and the degree to which they can be compared meaningfully with values measured in solid rock, are not clear and they should therefore be treated with caution. In addition, Loch Ness overlies the Great Glen fault which may act to focus or disperse heat locally and may therefore not be a good indicator of background regional heat flow.
- Four values come from radiogenic granite in the East Grampians region and will be influenced by local heat production, so might not be representative of background heat flow.
- Fifteen values are from boreholes in sedimentary rocks of Carboniferous/Devonian age. The temperature of these rocks may have been affected by large-scale convective transfer of heat in groundwater.
- The remaining seven measurements are from metamorphic rocks, and although these rocks have low permeability there is a growing body of evidence that suggests crystalline rocks may be affected to some degree by convective heat transfer. A value of 29 mW m$^{-2}$ from Tilleydesk (Ellon) was included in the Burley et al. (1984)\(^{[6]}\) data but was not formally reported by the group that measured it (Oxford University Heat Flow group), presumably because it is a suspect value.
- In all parts of Scotland, the geothermal gradient in the near-surface is likely to be perturbed by climate warming since the last glaciation. This is discussed below.

In a subsequent version of the Geothermal Catalogue (Rollin 1987)\(^{[3]}\) there are two additional heat flow measurements for Scotland (in Selkirk and Edinburgh), not included in previous analysis.

The heat flow values for Scotland presented in Gillespie et al. (2013)\(^{[1]}\) range from 29 to 82 mW m$^{-2}$; with a mean of 56 mW m$^{-2}$ and median of 57 mW m$^{-2}$. If the potentially anomalous Tilleydesk (Ellon) value is removed then the mean value for Scotland increases to 57 mW m$^{-2}$ and the minimum value is 37 mW m$^{-2}$ (Gillespie et al., 2013)\(^{[1]}\).

**Glasgow area**

There are no available heat flow measurements in the Clyde Gateway area; therefore data have been considered within 20 km of the boundaries of the Clyde Gateway area (Glasgow area). There are four heat flow and thermal conductivity measurements for the Glasgow area (Figure 48 and Table 15); all are within the north and west of the city. In comparison to data used for the heat flow map of the UK (Figure 47) these measurements are all from boreholes that are relatively shallow (Table 15).
Table 15  Heat flow measurements in the 20 km zone around the Clyde Gateway area. 
Note there is no temperature information for the Hurlet borehole.
The distribution of thermal conductivity with depth in the sedimentary crust is one of the major uncertainties in temperature predictions to depths >2 km (Rollin, 1987[3]). There are 23 borehole measurements of rock thermal conductivity in Rollin (1987)[3] for Scotland. Table 1 and Table 2 in Gillespie et al. (2013)[11] show values reported for common rock types (reported in Lee et al. 1984[11] and Wheildon et al. 1984[12]) and for seven broad categories of bedrock in Scotland, respectively. Mean thermal conductivities are also provided for specific lithologies by Rollin (1987)[3] in Table 3. Browne et al. (1985)[9] describe how the variation in conductivity for each lithology in the Upper Palaeozoic in the Midland Valley is considerable and, in addition, the proportion of rock-types in any formation is very variable. The ‘assumed values have been arrived at in a subjective manner, so that
it is difficult to assess appropriate errors on these'. The values and standard deviations are: Coal Measures 1.91±0.25 W m⁻¹ °C⁻¹, Passage Group 2.91±0.15 W m⁻¹ °C⁻¹, and Lower Carboniferous 2.12±0.25 W m⁻¹ °C⁻¹ (Browne et al., 1985).

Figure 47 shows that heat flow appears to be slightly higher in the central part of the Midland Valley, than in the surrounding area where a 60 mW m⁻² contour encloses a cluster of values, some of which are in Glasgow (Gillespie et al., 2013). Browne et al. (1987) suggest that heat flow is possibly slightly higher in the west than in the east of the Midland Valley. Mean heat flow for Glasgow, using the lower and higher values provided respectively for South Balgray and Blythswood (Table 15), would be 59.7 and 63.5 mW m⁻² with a standard deviation of 5.4 and 5.9 mW m⁻². The difference between these heat flow estimates, provided in Burley et al. (1984), result from differences in estimates of conductivity used in the heat flow calculations. One value is from Benfield (1939), who used thermal conductivities of core samples from the Boreland Borehole (Edinburgh, GR NT 3304, 6942) measured using the ‘divided bar equipment’. The other value is from Anderson (1940), who used estimates of thermal conductivity from core samples from the Boreland Borehole measured by ‘Bullard’, also using the ‘divided bar equipment’, in conjunction with data from British Association Reports (1880 and 1882). Rollin (1987) and Wheildon and Rollin (1986) chose to use the lower of the two values of heat flow, whereas Browne et al. (1985) and Gillespie et al. (2013) used the higher values of heat flow for these boreholes (Table 15). The only justification for this is in Browne et al. (1985) where these values are stated as ‘most reliable determination’ in Table 1. However, since the data quality is only rated as C, and the thermal conductivity was not measured in the same borehole, the heat flow at Maryhill and Hurlet should be considered as more reliable estimates. This would suggest a heat flow of 61.5 mW m⁻² for the Glasgow area. This value is slightly higher than the background heat flow for Scotland, 56 and 57 mW m⁻².

A number of reports and papers in the mid-1980s proposed a model to explain the assumed heat flow anomaly in the Midland Valley through regional upflow of groundwater (Browne et al., 1987; Lee et al., 1987; Robins, 1988). Downward flow is thought to predominate in areas of recharge along the southern and northern margins of the Midland Valley where higher elevation provides a higher fluid potential (Robins, 1988). While this model is consistent with topography and the configuration of aquifer units, Browne et al. (1987) state that the supporting evidence is inconclusive, and deep groundwater circulation is likely to be moderate in volume and limited to isolated discrete pathways. Robins (1988) argues that hydrochemical and isotopic data to support this theory are sparse because upwelling deep waters tend to mix with shallow near-surface waters. Other possible reasons for higher heat flows include; thinner crust, more radioactive granitic rocks within the crust, or continued heat flow from Cenozoic igneous activity (Browne et al., 1987).

It is known that past climate change has affected the temperature at the Earth’s surface and therefore the temperature distribution at depth (Westaway and Younger, 2013 and Busby et al., 2015). Each change in surface temperature will propagate into the ground, but the amplitude of the change will decrease exponentially with depth and there will be a time lag with perturbations at surface and at depth (Busby et al., 2015). With depth, this climatic impact on temperature will decrease. As such, the geothermal gradient measured in a shallow borehole would indicate a lower heat flow than exists. Westaway and Younger (2013) proposed that the heat flow measurements presented for the UK in Downing and Gray (1986), the geothermal catalogue and Busby (2011) have therefore been systematically underestimated. Busby et al. (2015) showed that when palaeoclimate corrections are applied to heat flow values in the East Grampians region of Scotland, there is an increase in heat flow of 25%. This effect is particularly acute when calculating heat flow in shallow boreholes (e.g. Westaway and Younger, 2013) such as those listed in Table 15. For Scotland, Westaway and Younger (2013) estimated there may be an additional 18.0 mW m⁻² heat flux in a very shallow borehole with rocks with thermal conductivity of 3 Wm⁻¹ °C⁻¹. For a 1 km deep
borehole the correction would reduce to 13.5 mW m$^{-2}$ if the heat flow had been calculated as the average for the whole depth of the borehole, or 8.8 mW m$^{-2}$ if it had been calculated from temperature measurements over a limited range of depths at the bottom of the borehole (where there is a smaller impact of paleoclimates). For a 1.5 km deep borehole the corrections would be 9.1 mW m$^{-2}$ and 0.2 mW m$^{-2}$ respectively (Westaway and Younger, 2013).

**Temperature**

The geothermal gradient, and hence temperature at a given depth, depends on the heat flow, thermal conductivity of the rock and groundwater flow (convection). Available temperature data measured in onshore boreholes were collated and reported in the Geothermal Catalogue for the UK. Version two (Burley et al., 1984[6]) is commonly quoted since it is cited in ‘Geothermal Energy; The potential in the United Kingdom’ (Downing and Gray, 1986[8]). However, there are additional data in Version 3 (Rollin et al., 1987[3]). More recently data have become available from Hard Copy temperature logs in the BGS archive, and the BGS National Petrophysical Data Archive. These, and additional data sources for temperature, are discussed in the following section.

The BGS Catalogue of Geothermal Data for the UK (Burley et al., 1984[6]) collated available borehole temperature data as part of the 1977 to 1984 Geothermal Energy Programme of the British Geological Survey, supported by the UK Department of Energy and Commission of European Communities (C.E.C.). The catalogue includes a list of borehole temperature data for 61 boreholes in onshore parts of Scotland; these include many of the boreholes from which heat flow values have been calculated. In most cases, the temperature measurement has been made at, or near to, the bottom of the borehole. Whereas most of the available heat flow data come from depths of less than 400 m below ground surface, the onshore borehole temperature data extend to a depth of around 1,300 m. Boreholes are clustered mainly in Caithness, the East Grampians region, and in the Midland Valley. Temperature data for onshore boreholes in Scotland from Burley et al. (1984)[6] are summarised in Gillespie et al. (2013[1]; Table 4). 17 additional borehole temperature-depth measurements located on the Ordnance Survey NS sheet (west Midland Valley) were included in Rollin (1987)[3], the third revision of the geothermal catalogue.

Busby et al. (2011)[2] produced new temperature maps for the UK using data from the Geothermal Catalogues for the UK, and new data from the BGS National Petrophysical Data Archive and Hard Copy temperature logs. The National Petrophysical Data Archive captured sub-surface temperature data added to the digital archive since the compilation of the Geothermal Catalogues. Hard Copy petrophysical log data are derived mostly from the hydrocarbon industry, British Coal exploration, or from BGS’s own onshore research (Busby et al., 2011[2]). Temperature values were extracted at intervals of 100 m bgl, taking into account any deviations of the well from vertical. Due to issues with logging, the depth interval was bracketed by ± 5 m (e.g. from 195 to 205 m below ground level, bgl). Due to time constraints, not all logs could be examined and so an approach based firstly on accessibility and quality of data, and then on maximum depth coverage and geographical location in relation to existing data points, was applied. These data were used to compile maps of temperatures at depths below ground level of 100, 200, 500 and 1000 m. From these data, regional trends and anomalies have been defined and a UK-wide geothermal gradient of 28°C km$^{-1}$ was calculated for the upper 1 km of the sedimentary crust — slightly above the previously quoted value of 26°C km$^{-1}$. The distribution of the measured temperature data is variable. For the 100 and 200 m depth intervals there is reasonable coverage across the Central Belt of Scotland; however for the deeper 500 and 1000 m depth intervals the majority of the data are concentrated in central and southern England.

From the data in Burley et al. (1984)[6], Gillespie et al. (2013)[1] calculated an average temperature gradient for each borehole in Scotland using the surface temperature, the borehole temperature at
depth, and the depth at which the latter was measured. The average temperature gradient values for all 61 onshore boreholes in Scotland range from 3.7 to 45°C/km; the mean is 22.5°C/km, and the median is 21.5°C/km. The wide range of average temperature gradient values suggests that the gradient in any one borehole is affected by a range of local factors. However, plotted together as temperature versus depth (T-z) the data display a trend defining a temperature gradient of 30.5°C/km which persists throughout the entire depth range intersected by these boreholes (down to c.1500 m). When extrapolated, it was found that the best-fit line through all the data intersects the surface at approximately 4.0°C; significantly below the current annual average surface temperature in Scotland (taken to be 9.0°C, from the average of all the surface temperature data listed in Burley et al., 1984\textsuperscript{[6]}).

This implies that the top end of the geothermal gradient (the part that is typically measured in shallow boreholes) is not simply a continuation of the deeper trend; the gradient must steepen (i.e. the rate of increase in temperature with depth will appear to be smaller) in the near subsurface (Gillespie et al., 2013\textsuperscript{[1]}). This supports the theory that Holocene warming has had an impact on near-surface temperatures in Scotland (Westaway and Younger, 2013\textsuperscript{[4]} and Busby et al., 2015\textsuperscript{[5]}). Hence, measurements of the geothermal gradient made in individual shallow boreholes are likely to underestimate the geothermal gradient at depth. Browne et al. (1985\textsuperscript{[9]}, 1987\textsuperscript{[13]}) reported that the average temperature gradient (based on borehole temperature versus depth [T-z] data) for boreholes in the Midland Valley was 22.5°C/km. This is significantly lower than the value suggested by Gillespie et al. (2013\textsuperscript{[1]}) for onshore boreholes in Scotland using the same dataset. The difference is because the data have been interpreted in different ways: Browne et al. (1987\textsuperscript{[13]} ‘pinned’ the top of their interpreted geothermal gradient to a surface temperature of 10°C (representing the present day surface temperature at Grangemouth), whereas Gillespie et al. (2013\textsuperscript{[1]}) used only temperatures measured at or near the base of boreholes to calculate an ‘averaged geothermal gradient’. When considering both onshore and offshore boreholes (n=133), ranging up to 5 km in depth, Gillespie et al. (2013\textsuperscript{[1]}) found the geothermal gradient to be slightly curved, with an increase at depth, from 30.5°C/km in the shallowest third, to 46.7°C/km in the deepest third. These values equate to temperatures of 100°C and 150°C at depths of approximately 3.0 and 4.0 km, respectively. However, the data defining the trend come mainly from offshore boreholes and caution should be taken when extrapolating the same gradient onshore. Gillespie et al. (2013\textsuperscript{[1]}) suggested that this increase in temperature gradient with depth could result from the impacts of palaeoclimate, or from the proximity of some offshore areas to the continental margin where the crust might be thinner and heat flow therefore higher. Even if onshore settings do not follow the higher temperature gradient of offshore settings below 1.5 km, the gradient of 30.5°C/km defined by the data from onshore boreholes suggests temperatures could be around 150°C at 5 km depth in onshore areas. The gradient for onshore data is defined mainly by boreholes in the Midland Valley, so the level of confidence attached to an extrapolation to 5 km is highest for that area (Gillespie et al.,2013\textsuperscript{[1]}).

**Glasgow area**

There are 13 temperature measurements within 20 km of the Clyde Gateway area (Table 16); two are from temperature logs, three from equilibrium temperature measurements, four from bottom hole temperatures, three from Drill Stem Tests (DST), and one is from minewater temperature measurements. Most data were extracted from the Geothermal Catalogue Version 2 (Burley et al., 1984\textsuperscript{[6]}), an additional site (Salsburgh 2) was available in Version 3 (Rollin, 1987\textsuperscript{[3]}) and another (Bargeddie 1, with two DSTs) was available in the DECC Onshore Wells Archive accessible to BGS. A number of temperature measurements from the Baseline Geochemical Survey were available but discounted due to the distance between the borehole outlet and sampling point. There were no additional temperature measurements in this area from the National Petrophysical Archive or hard copy logs. However, hard copy logs were not included in the analysis if they appeared to be
anomalous because this might represent groundwater flow rather than background geothermal gradients (C. Gent, pers comm.).

The average geothermal gradient for the measured depth/temperatures in the Glasgow area is 30.2°C/km with an un-pinned surface temperature of 7.3°C (Figure 49). However, for individual boreholes, the measured temperature gradient varies between 6 and 38.4°C/km. There are no clear spatial patterns in the geothermal gradient measured at individual boreholes (Figure 48). However, due to differences in surface temperatures it is difficult to compare measurements of geothermal gradients made for individual boreholes. The scatter of data in Figure 49 shows that there could be some local variability in the geothermal gradient due to local effects, such as groundwater flow, lithology or differences in heat flow.

The Highhouse Colliery plots relatively closely to the average geothermal gradient line (Figure 49), indicating that the temperature in the mine might also reflect the geothermal gradient for Glasgow.

Table 16  Boreholes with temperature measurements within 20 km of the Clyde Gateway area. LOG is log temperature, EQM is equilibrium measurement, MWT is minewater temperature. For bargeddie 1, no surface temperature was provided; therefore the interception temperature from the average geothermal gradient was used (Figure 49).

<table>
<thead>
<tr>
<th>Borehole name</th>
<th>Unit</th>
<th>Type</th>
<th>X</th>
<th>Y</th>
<th>Start height (m aOD)</th>
<th>Depth (m bgl)</th>
<th>Temp (°C)</th>
<th>Geothermal gradient (°C/km)</th>
<th>Heat flux (W m⁻¹ K⁻¹)</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hallside</td>
<td>Scottish Upper Coal Measures Formation</td>
<td>LOG</td>
<td>266940</td>
<td>659750</td>
<td>54</td>
<td>350</td>
<td>11.8</td>
<td>6</td>
<td>N/A</td>
<td>Burley et al. (1984)[6]</td>
</tr>
<tr>
<td>South Balgray</td>
<td>Clyde Plateau Volcanic Formation, Limestone Coal</td>
<td>EQM</td>
<td>250000</td>
<td>675000</td>
<td>30</td>
<td>160</td>
<td>15.3</td>
<td>45</td>
<td>72</td>
<td>Burley et al. (1984)[6]</td>
</tr>
<tr>
<td>Blythswood</td>
<td>Clackmannan Group Type</td>
<td>EQM</td>
<td>250030</td>
<td>668230</td>
<td>2</td>
<td>105</td>
<td>12</td>
<td>37.1</td>
<td>59</td>
<td>Burley et al. (1984)[6]</td>
</tr>
<tr>
<td>Queenslie</td>
<td>Coal Measures Group Limestone Coal</td>
<td>BHT</td>
<td>264660</td>
<td>665980</td>
<td>78</td>
<td>691</td>
<td>36</td>
<td>38.4</td>
<td>N/A</td>
<td>Burley et al. (1984)[6]</td>
</tr>
<tr>
<td>Maryhill</td>
<td>Clackmannan Group Type</td>
<td>EQM</td>
<td>257180</td>
<td>668560</td>
<td>55</td>
<td>303</td>
<td>20</td>
<td>34</td>
<td>63</td>
<td>Burley et al. (1984)[6]</td>
</tr>
<tr>
<td>Clachie Bridge</td>
<td>Lower Carboniferous, Upper Old Red Sandstone</td>
<td>LOG</td>
<td>264470</td>
<td>683680</td>
<td>271</td>
<td>300</td>
<td>13.2</td>
<td>16</td>
<td>N/A</td>
<td>Burley et al. (1984)[6]</td>
</tr>
<tr>
<td>Salsburgh 1A</td>
<td>Carboniferous Limestone</td>
<td>BHT</td>
<td>281660</td>
<td>664860</td>
<td>223</td>
<td>883</td>
<td>30</td>
<td>24.1</td>
<td>N/A</td>
<td>Burley et al. (1984)[6]</td>
</tr>
<tr>
<td>Salsburgh 1A</td>
<td>Carboniferous Limestone</td>
<td>DST</td>
<td>281660</td>
<td>664860</td>
<td>223</td>
<td>874</td>
<td>29</td>
<td>23.2</td>
<td>N/A</td>
<td>Burley et al. (1984)[6]</td>
</tr>
<tr>
<td>Salsburgh 2</td>
<td>Carboniferous Limestone</td>
<td>BHT</td>
<td>282110</td>
<td>663850</td>
<td>223?</td>
<td>1104</td>
<td>44</td>
<td>32.1</td>
<td>N/A</td>
<td>Rollin et al. (1987)[3]</td>
</tr>
</tbody>
</table>
Abandoned mines can provide access to thermal reservoirs from which to extract heat. Glasgow is underlain in many parts by a network of abandoned mines from which coal, ironstone and other minerals were extracted. An open-loop Ground Source Heat Pump (GSHP) installation utilising mine water at Shettleston, in east Glasgow, c.1.5 km to the north-west of Clyde Gateway, has been operating since the year 2000. It is a small scheme, serving 16 dwellings over an area of 1600 m², using water from 100 m depth and 12°C, pumped at 5 to 10 l/s (Figure 50). The water is returned at 3°C (Banks et al., 2004[18]).

Similar to other mining areas, the underground mine workings at Clyde Gateway exist over a range of depths, meaning that the temperature could vary quite significantly between the uppermost and lowermost levels due to the geothermal gradient. Mines that extend to relatively deep levels, can provide relatively easy access (e.g. via remnant shafts) to higher temperature water. The shallower mine levels can be utilised for re-injection of cooled water. A relatively large system of abstraction and injection (and heat storage) at different depths within mines is used for a district heat system for municipal and some private buildings in the town of Heerlen, in the Netherlands (see Verhoeven et
Minewater temperatures for nine boreholes in the Midland Valley have a fairly narrow temperature range — from 12 to 21°C, with a mean (and median) of 17°C (Gillespie et al., 2013).

Figure 50 shows that there is little correlation between temperature and depth. Preferential fluid flow pathways can form through mine tunnels and shafts; thus in some places mine water might not be in thermal equilibrium with the geothermal gradient. However, there are few data points and a limited depth of measurement (between 200 and 800 m bgl). It is also not simple to predict the temperature of water pumped from a borehole, as water of different temperatures may be entering the borehole at different depths (Gillespie et al., 2013).

Figure 50  Measured water temperature with depth from mines in the Midland Valley of Scotland (Burley et al., 1984).

Ó Dochartaigh (2009) described temperature data collected as part of a project establishing natural groundwater chemistry in aquifers across Scotland (Baseline Scotland). In autumn 2008, new groundwater samples were collected from boreholes abstracting from Carboniferous sedimentary aquifers across the Midland Valley. Four samples were collected of mine water, either pumped or flowing under gravity from abandoned mine workings. Two of the measured pumped
minewater temperatures in the Baseline Scotland project were 11.7 and 14.5°C, similar to the
typical temperature of natural groundwater from Carboniferous aquifers in the Midland Valley. The
third, at 19.2°C, from Polkemmet, was pumped from an existing mine shaft, although the depth was
not known. The single measured temperature of a gravity minewater flow was 9.8°C. The Coal
Authority also has a database of passive discharges from abandoned mines in Scotland, which at the
time Ó Dochartaigh had permission to use on the Baseline Scotland project. Only one of these
recorded discharges is in Glasgow; on the outskirts in Swinton, by Coatbridge.

The single record for minewater temperature in Glasgow is the Highhouse Colliery, Bearsden
(Northwest Glasgow, Figure 49). Here, a temperature of 18°C was measured at 436 m depth
(Gillespie et al., 2013[1]). It is not clear to what degree this value is influenced by the temperature of
the surrounding rocks.

**Hot Sedimentary Aquifer (HSA) geothermal**

In places where aquifers of sufficient permeability and thickness exist at depth, heat energy can be
extracted. The Midland Valley is the largest onshore area in Scotland to be underlain by sedimentary
rocks (Gillespie et al., 2013[1]) some of which might be aquifers at depth. However, their properties
at depth are still largely unknown. Interpretation of temperatures is complicated by groundwater
flow in areas of active coal mines. Aquifer properties are discussed above (Section 4). The
geothermal potential of HSA was investigated by Browne et al. (1985)[9] and Browne et al. (1987)[13].
They identified the possibility that the Knox Pulpit Formation could be buried beneath Glasgow, with
thicknesses up to 170 m. The temperature at the top of the group was expected to exceed 40°C.
Where yield permits, heat pumps could be used to extract the heat energy. Other Carboniferous
strata are considered to have limited HSA potential due to low intergranular permeability (Browne
et al., 1985[9]). However fractures might increase secondary permeability in some places.

**Faults and fluid flows**

Faults can have a significant impact on subsurface temperatures due to their influence on rock
permeability and resulting impacts on fluid flow pathways and heat transport. Faults are common
throughout the Midland Valley. Faults can behave as pathways or baffles to water (or both
simultaneously). Specific lithologies deform differently when subjected to stress, resulting in
different permeability structures within fault zones.

Fault cores in (macroscopically) brittle rocks can comprise a combination of fault gouge, cataclasite,
breccia, mylonite, discrete slip surfaces, and relatively cohesive lenses or blocks. Fault damage
zones in brittle rocks tend to fracture, creating breccia or joints (Bense et al., 2013[21]). Often, the
damage zone around the fault core can be much more extensive and hydraulically more important,
contributing more towards bulk permeability than the core (10’s to 1000’s of meters in thickness
perpendicular to the fault strike compared with 0.1 to 10 m thickness). A model of fault hydraulic
behaviour developed by Caine et al. (1996)[22] projects the propensity for a fault to behave as a
conduit/barrier according to the ratio of specific fault zone elements.

In clastic rocks, strain can be accommodated by (sometimes multiple) deformation bands in both the
fault core and damage zone (Antonellini et al., 1995[22]; Aydin, 1978[23]). These are thin bands (<2 cm
thickness) in which cataclasism and particulate flow occur (breakage and rolling/sliding of grains),
acting to reduce pore space and thus permeability. Fractures are less common in these rocks. If
there is a sufficient proportion of clay in the protolith of clastic rocks, clay can be smeared through
the fault core, forming a seal of low permeability rock if continuous (Yielding et al., 1997[22]). Clay
smears can also be found in carbonate rocks. As a result of these processes, faults in clastic rocks
often reduce permeability (Gibson, 1998).

Certain lithologies — carbonates in particular — may also be karstified, whereby permeability is increased further by the dissolution of the rock along fractures (Billi, 2005). Conversely, over time, mineral-saturated fluids can precipitate cements in pores and/or fractures and effectively become resealed, reducing fault permeability (Micarelli et al., 2006) and forming baffles to fluid-flow. Each time the fault deforms (through tectonic stresses, or even due to stress perturbations such as unloading after glaciations or sub-surface stress changes) fractures may open and permeability can increase again (Knipe, 1997). Chemical reactions will begin again as groundwater enters the fractures. As a result, faults that have deformed more recently are more likely to be permeable. Barton et al. (1995) also found that normal faults optimally oriented to the current stress field, i.e. ‘critically stressed’ and therefore more likely to slip, were also more permeable than those not critically stressed.

Browne et al. (1985) suggested most of the fault structures in the Midland Valley are normal faults, but high angle reversed faults also occur. They suggest that the history of the faults is complex and many structures have undergone different phases of movement. The truncation of some faults buried by younger sediments and volcanic rocks suggest that some became inactive after the early Carboniferous. In the Strathmore area, Devonian rocks are cut by sub-vertical orthogonal joint systems. Fault planes range from single slip planes to broken zones with associated fault breccias. Tests showed that water was usually derived from one or possibly two major fissure zones, with recharge either via fault zones or along dipping planes (Browne et al., 1985). Pumping tests and geophysical logs suggest that major water-bearing fissures occur down to depths of 125 m (Browne et al., 1985). The proximity of the coast and the Highland Boundary Fault may have caused groundwater to flow to effect the measured heat flow value at Montrose (Browne et al., 1987). No data have been located in the Glasgow area.

**Geothermal data gaps**

In summary, there are no heat flow or temperature data in the Clyde Gateway area. 13 borehole temperature measurements in the 20 km area surrounding the Clyde Gateway area of interest indicate an average geothermal gradient of 30.2°C/km with a surface temperature of 7.3°C (Figure 49). Four heat flow measurements in the same area indicate a heat flow between 59.7 and 63.5 mW m$^{-2}$ (standard deviation 5.4 and 5.9 mW m$^{-2}$). It has been suggested that heat flow measurements from shallow boreholes in the UK, such as those in Glasgow, have underestimated heat flow (e.g. Westaway and Younger, 2013; Busby et al., 2015). The impacts of palaeoclimates and recent warming on heat flow and geothermal gradients is therefore a key research question for assessing the geothermal potential of Glasgow, and other areas in the UK. This will require temperature and heat flow (and thermal conductivity) measurements at a range of depths throughout a number of deep (>2 km depth) boreholes.

All heat flow measurements are currently from the north-west of Glasgow. There is only one temperature measurement in the south of Glasgow. Heat flow and temperature measurements in the south and east of the city, including in the Clyde Gateway area, would greatly improve the data coverage.

The single measurement of minewater temperature, at Highhouse Colliery in the north-west of Glasgow, was 18°C at 436 m depth. It is not clear how closely this represents either the geothermal gradient, other minewater temperatures or temporal changes within mines. In order to properly assess minewater geothermal potential in Glasgow, additional temperature measurements in mine workings are needed with a good geographic spread and at different depths within the mines and
over a sufficient time period in order to address these questions.

There is very little data available regarding the hydraulic behaviour of faults in the area of interest. Since faults can have a key role in controlling fluid flow pathways and patterns on a local and regional scale, elucidation of their behaviour will be key to future investigations.

Due to the lack of hydrogeological and geothermal data for the study area it has not been possible to identify a geothermal or hydrogeological model for the Clyde Gateway area at this stage. However, one hypothesis is that the slightly higher geothermal gradient in Glasgow and the central Midland Valley might result from regional upflow of groundwater (Browne et al., 1987[13]; Lee et al., 1987[16]; Robins, 1988[12]). This hypothesis could be used as a starting point for investigations. It would also be key to investigate the impact of mine workings on these natural flow pathways.

At this stage a geothermal feasibility study was not conducted due to the significant uncertainties associated with heat flow and temperature measurements in the area. However, there are a number which have attempted to do so (Ellen, et al., 2015[31]; Ellen and Loveless, 2015[32]; MacNab, 2011[33]). Additional constraint of the geothermal properties of the area would enable realistic feasibility studies to be conducted for minewater potential and HSA.

Footnote

1. ↑ Note a new version uplifted for climatic effects was published by Busby & Terrington 2017 DOI 10.1186/s40517-017-0066-z

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