Study into the Potential for Deep Geothermal Energy in Scotland

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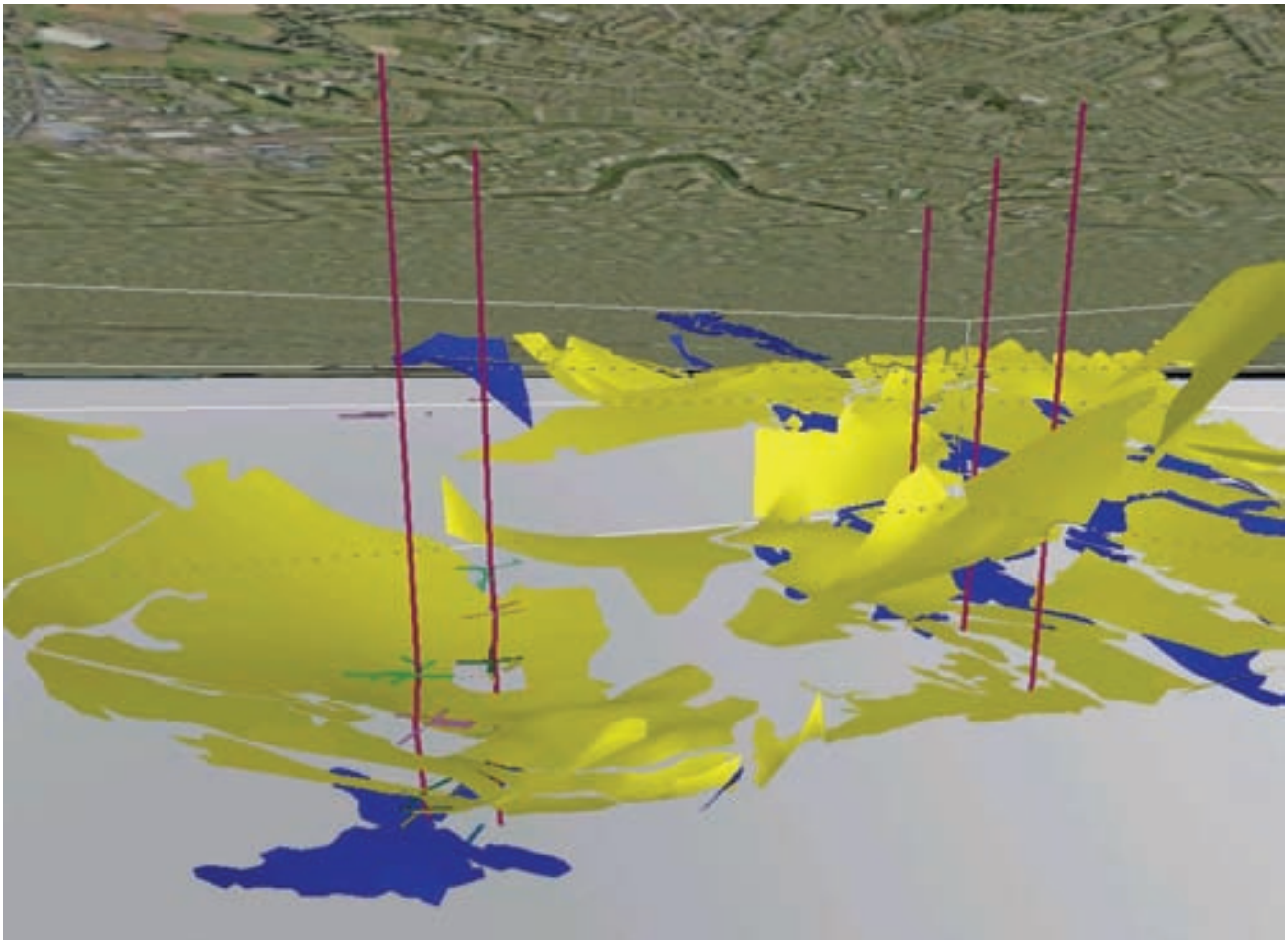

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Deep geothermal energy potential in Scotland

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Keywords

Geothermal energy, Scotland, minewater, Hot Sedimentary Aquifer, HSA, Hot Dry Rock, HDR, BGS, AECOM, Scottish Government.

Front cover

3D model of coal seams, mine shafts and mine roadways under the east end of Glasgow. Viewed in Virtalis/BGS GeoVisionary software.

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Foreword

This report contains the BGS contribution to a collaborative project between AECOM and BGS to produce a qualitative assessment of deep geothermal energy potential in Scotland for the Scottish Government Study (Scottish Government Contract Ref. CR/2011/07) into the Potential for Deep Geothermal Energy in Scotland. BGS was asked to provide the Stage One deliverable —Identifying and assessing geothermal energy potential”, comprising an assessment of areas in Scotland most likely to hold deep geothermal resources based on existing geological and geothermal data sets. AECOM undertook the Stage 2 deliverable —Development of Key Policy Options” in which policy options and key actions are identified that the Scottish Government can potentially implement to encourage commercial exploitation of the available geothermal resource.

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In addition to the authors of this report, several other BGS staff have contributed to this study, namely Jon Busby, Diarmad Campbell, Adrian Walker and Bill McLean.

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INTRODUCTION

Geothermal energy is simply the natural heat that exists within our planet. In some parts of the world the existence of a geothermal energy resource is made obvious by the presence of hot springs, and such resources have been exploited in various ways for millennia. More usually, there is no direct evidence at Earth‘s surface of the vast reservoir of stored heat below, and geothermal energy has remained largely ignored and untapped in most parts of the world. Now, its potential as a renewable source of energy is being recognised increasingly, and technologies and concepts for exploiting it are developing rapidly along two lines: low enthalpy (low temperature) resources, which exploit warm water in the shallow subsurface to provide heat either directly (as warm water) or indirectly (via heat exchange systems); and high enthalpy (high temperature) resources, which yield hot water, usually from deeper levels, that can be used to generate electricity.

The potential for harnessing electricity from geothermal energy has long been recognised; the potentially substantial reserves, minimal environmental impact, and capacity to contribute continuously to base load electricity supply make it an extremely attractive prospect. The ongoing drive to develop renewable sources of energy, coupled with anticipated technological developments that will in future reduce the depth at which heat reservoirs are considered economically viable, means there is now a pressing need to know more about the deep geothermal energy potential in Scotland. This report contains the British Geological Survey (BGS) contribution to a collaborative project between AECOM and BGS to produce a qualitative assessment of deep geothermal energy potential in onshore Scotland for the Scottish Government. BGS‘s role is to provide the Stage One deliverable —Identifying and assessing geothermal energy potential”, comprising an assessment of areas in Scotland most likely to hold deep geothermal resources based on existing geological and geothermal data sets.

The report is divided into two parts. Part 1 sets out the background to geothermal energy, describes the geological context, and presents an analysis of the size and accessibility of the heat resource in Scotland based on existing geothermal data. The potential for exploiting deep geothermal energy in three settings in inshore areas of Scotland (abandoned mine workings, Hot Sedimentary Aquifers, and Hot Dry Rocks) is examined in Part 2.

THE HEAT RESOURCE IN SCOTLAND

Scotland sits on a geologically stable part of Earth‘s crust and has none of the obvious features - such as hot springs or volcanic activity - that would indicate the presence of a substantial heat resource in accessible parts of the subsurface. The mean of 35 heat flow values[1] reported for Scotland of 56 mW m^{-2} is lower than the mean value for all continents (65 mW m^{-2}), and significantly lower than values usually associated with exploitable resources of deep geothermal energy.

[1] Heat flow is the standard measure of the amount of heat travelling through Earth‘s crust, and heat flow measurements (usually made in shallow boreholes) are the standard means of gauging the size of the heat resource at depth. Heat flow values are generally expressed in milliwatts per metre square (mW m^{-2}).

In order to calculate a heat flow value, the geothermal gradient (the rate at which temperature increases with depth in the Earth‘s crust) must be measured in a borehole. Within the last decade, research has shown that warming of the ground surface since the last period of widespread glaciation (the ‗Ice Age‘) has perturbed the geothermal gradient within the top 2 km of the crust, with the result that measured geothermal gradient values (and therefore heat flow values) are reduced. Scotland was strongly affected by the ‗Ice Age‘ glaciations, so existing heat flow measurements in Scotland probably significantly underestimate the true size of the heat resource that exists beneath the climate-affected zone. Published data suggest that recent changes in the climate may have suppressed near-surface heat flow by as much as 60% in some parts of northern Europe and North America. Preliminary, unpublished work by BGS indicates that heat flow values in the East Grampians region of Scotland may be suppressed by up to 29%. These findings suggest that heat flow below the climate-affected zone in Scotland (which may extend to a depth of around 2 km) is significantly greater than was previously assumed.

Temperature data measured in boreholes provide the best currently available alternative means of examining the size and distribution of the heat resource beneath Scotland. Borehole temperature data from 133 boreholes ranging up to 5 km deep and representing both onshore and offshore parts of Scotland display a well-defined trend when plotted as temperature versus depth. The geographical extent of the data and the consistency of the trend throughout its depth range suggest the trend may represent a regional temperature gradient for Scotland. The gradient is slightly curved and increases with depth, from 30.5°C/km in the shallowest third to 46.7°C/km in the deepest third. These values, which equate to temperatures of 100ºC and 150ºC at depths of approximately 3.0 and 4.0 km, respectively, suggest there is a significantly larger heat resource at accessible depths beneath Scotland than has been suspected previously. However, the data defining the trend come mainly from offshore boreholes in sedimentary rocks, and caution should be exercised in extrapolating the same gradient to deep levels onshore, particularly in crystalline rocks. More research is needed to test this result; nevertheless, the borehole temperature trend suggests the temperature gradient in the crust beneath Scotland may be significantly higher and more consistent regionally than has been recognised hitherto.

The regional geothermal regime beneath Scotland is still relatively poorly understood. A better understanding of the regional distribution of heat, both laterally and vertically, in shallow parts of the crust is needed before decisions are made regarding the location and design of more detailed, site-specific studies.

Recommendations for further work:

R1 model the effect on the geothermal gradient of post-glacial warming

R2 improve the heat flow dataset for Scotland

R3 extend the borehole temperature dataset (bottom-hole temperature versus depth) to include all available data for Scotland.

GEOLOGICAL SETTINGS FOR EXPLOITING GEOTHERMAL ENERGY

The geothermal heat resource beneath Scotland can be considered in terms of three main settings: abandoned mine workings (low enthalpy), hot sedimentary aquifers (low and possibly high enthalpy), and hot dry rocks (high enthalpy).

Abandoned mine workings

Scotland's Midland Valley is underlain in many parts by a network of abandoned mines. These once employed thousands of miners to extract coal, ironstone and other minerals and are the basis and location of many towns and villages. They provided the energy and raw materials that powered industry in the 19th and 20th centuries, and the fuel to heat domestic properties. With industrial change and economic decline the mines closed so that there are no underground mines still in operation. The mines could play an important role in future in energy supply, providing access to thermal reservoirs which could help to heat homes and other buildings, and contribute to the energy mix of a low carbon Scottish economy based substantially on renewable energy.

Two installations of GSHPs currently tap mine water in Scotland: Shettleston in east Glasgow and Lumphinnans in Fife. Both are small schemes, each serving less than 20 dwellings, and have been operating since 1999–2000.

Most mine workings were collapsed in a controlled way soon after the resource had been extracted, but these rubbly collapsed layers can store and transmit significant volumes of groundwater. Larger voids remain underground in the form of old mine shafts and roadways, as many of these were constructed to a high standard and are still propped open.

During their operation, very large volumes of water had to be pumped from the mines. This water, held naturally in the rocks as groundwater, entered the mine workings, but with pumping, the level at which groundwater occurred around the mines was greatly lowered so they could function in relatively dry conditions. When mining ceased, pumping ceased also in most instances allowing the natural levels of groundwater to re-establish. As a result, most of the abandoned mine workings become flooded, and remain so today. The abandoned mine workings now contain significant volumes of water. In addition and arguably more importantly, they provide potential access to the very much larger volumes of water held in the rocks within which the mines occur. The volumes of water in the surrounding rocks are of the order of 100 times greater than the volumes of water in the mine workings.

Therefore, the abandoned and flooded mine workings and their surrounding rocks have very large subsurface volumes, which in turn contain very large volumes of water. It is the water which and provides significant potential for heat exchange. This, and the associated potential high abstraction rates as a result of the mining-enhanced permeability, makes them potentially suited to large, open-loop ground source heat pump (GSHP) systems. These open-loop systems would not be open to the atmosphere as the chemistry of the mine waters, and particularly their potentially high iron content, could result in iron precipitation if exposed to atmospheric oxygen.

Mine workings typically worked several relatively flat lying seams of coal (etc) in a vertical succession. These often spanned a significant depth range (up to several hundred metres). This could enable water to be abstracted from one depth interval for example towards the bottom of the mine, and returned to the ground at a different depth for example at a significantly shallower depth and after heat has been extracted from the water. This vertical separation can be advantageous in increasing the time before the returned water, at lower temperature and shallower depth, starts to arrive at the point of abstraction where water warms at greater depth. This can in turn improve the efficiency of a scheme. Mines can extend to relatively deep levels, so in some cases they can provide easy access (e.g. via remnant shafts) to higher temperature water. For example, a borehole at the Solsgirth Colliery in Clackmannanshire recorded a temperature of 21.5 °C at a depth of 387 metres. Deep boreholes (800 metres) at Heerlen in the Netherlands intercepted water of about 35 °C.

In 2004, the Scottish National Mine Water Potential Study assessed the largest 62 coal mines in Scotland; the number of men that worked down the mine was used as a proxy for the volume of mine water that might be available. The study considered the potential for mine water heating at Shawfair, near Edinburgh, as part of a consideration of the wider potential across the Midland Valley of Scotland. It was calculated that mine waters could contribute up to 1,708 gigawatt hours (GWh) per annum of heat, if grants were provided. This equates to about 3% of their estimate of Scotland‘s total annual heat demand in 2004.

This assessment of the geothermal potential of mine water in Scotland draws on recent BGS work, including 3D modelling, and utilises other available data to provide an estimate of potential borehole yields and the extent of the likely resource across the Scottish coalfields. The appraisal is based on the best estimates of geological and hydrogeological properties of the mined areas, providing a different viewpoint from earlier studies. Ironstone and oil-shale mines within the Midland Valley also have the potential for use in mine water heat recovery. From BGS 3D modelling, borehole data, and Coal Authority extent-of-mining data, we estimate the volume of the mine-worked area (i.e. from the base of the mine workings to land surface) to be 600 km^3. It is this approximate volume of rock, and the mine workings themselves, that groundwater can be abstracted (pumped), and from which heat can be extracted.

The two key parameters which influence the potential for getting heat from mine waters are the flow rate at which water can be abstracted from the subsurface without significantly depleting the resource, and the temperature of that water.

It is very difficult to predict the likely flow rate (borehole yield) that a particular borehole might obtain due to the great variability in mining-enhanced aquifers, but analysis of available data has enabled us to establish a typical range of yield. In general, it is thought reasonable to expect a yield of about 10 litres per second (l/s) in mining-enhanced aquifers, from an individual borehole penetrating a reasonable water-saturated thickness of strata (minimum of 50 metres). For the purposes of the calculations of potential heat abstraction, a range of 5 to 25 l/s per borehole seems reasonable. Assuming that this yield could be achieved in boreholes spaced at 4 boreholes per km^2, we suggest that the groundwater could be exploited at a rate of 20 to 100 $l/s/km^2$. This rate of pumping would be far in excess of the natural recharge rate and would be unsustainable without re-injection of the water to the aquifer (ie. the shallow mine workings) after heat has been extracted.

The temperature of mine waters generally increases with depth according to the geothermal gradient. It is not simple, however, to predict the temperature of water pumped from a borehole, as water of different temperature may be entering the borehole at different depths. A compilation of mine water temperatures for boreholes in the Midland Valley shows a fairly narrow spread of temperatures from 12 to 21°C, with a mean (and median) of 17°C. However, this may not accurately reflect the higher temperatures that may occur in some of the deepest mine workings in Scotland.

We estimate that some 2.5 megawatts per kilometre square (MW/km^2) could be obtained on average using open-loop ground source heat systems in the mined areas of Scotland. Multiplying this value by the number of square kilometres in the mined area (4.8×10^3 km^2) gives a very approximate estimate of the accessible heat of 12 000 MW (12 GW). We consider this to be an approximate estimate of the maximum potentially accessible resource, i.e. how much heat energy could theoretically be extracted from all the mined areas of the Midland Valley, bearing in mind the geological constraints on how much water can in practice be abstracted.

On this basis, mine waters could theoretically provide the equivalent of approximately one third of Scotland‘s heat demand. However, the actual contribution is likely to be significantly less for three main reasons:

1. heat cannot be transported efficiently over large distances, so would only be used above or close to suitable mine workings (although many towns and villages in Scotland‘s Midland Valley lie directly above mine workings, reflecting their historic roots);
2. a proportion of mine workings will not be suited to heat extraction;
3. heat delivered by GSHP is most effectively used in new-build properties; existing building stock would likely require extensive upgrading to benefit from mine water heat.

We have not selected areas within the Midland Valley as having more favourable prospects for mine water heat recovery as economic and technical factors are likely to play a greater role in site selection.

Mine water in abandoned workings in Scotland‘s Midland Valley presents a potentially important geothermal resource which might be used (by heat exchange) for space and domestic hot water heating, and related uses. However, there are many assumptions and generalisations in this assessment and further work is recommended.

Recommendations

R4 One or more site-specific studies should be conducted utilising existing information (including Coal Authority and BGS data), developing a detailed 3D model of the mine workings, gathering new information on borehole yields and permeability, and assessing the technical feasibility of installing an open loop GSHP system perhaps in combination with other forms of energy. The Glasgow area would be an obvious target given the availability of BGS 3D geological models and other previous studies as well as the expected scale of the ongoing developments and urban regeneration.

R5 The GSHP industry should be encouraged to deposit key data on installed schemes in a national archive, similar to that for borehole data held by BGS to facilitate further modelling and potential exploitation of available thermal resources.

Hot sedimentary aquifers

Aquifers are bodies of permeable rock that can conduct significant quantities of groundwater. The largest and most conductive aquifers generally occur in sedimentary strata, and any of these that are hot enough and have sufficient productivity to constitute a potential geothermal resource can be termed a Hot Sedimentary Aquifer (HSA). HSA resources are likely to exist, in general, down to depths of around 4 km, and most will yield water in the temperature range 20–80ºC. The hot water can be used for heating, either directly or indirectly (by heat exchange). The first, and so far only, successful HSA system developed in the UK is in Southampton. Opened in 1986, the system exploits warm water (<80°C) at a depth of nearly 2 kilometres in sedimentary strata. A combined heat and power (CHP) system delivers sustainable supplies of heat (district heating), chilled water and electricity.

Most of Scotland (including much of the Highlands and Southern Uplands areas) is underlain by relatively impermeable crystalline (non-sedimentary) rocks, which have no HSA potential. The Midland Valley is the largest onshore part of Scotland to be underlain by sedimentary strata, and the best HSA prospects are likely to be here.

However, the Midland Valley is geologically complex, and it can be difficult to make geological correlations between boreholes and to extrapolate surface observations below the ground surface. Interpretation in some areas is complicated further by the influence on groundwater flow of abandoned and active coal mines. The aquifers are typically of variable lithology, intruded by relatively impermeable igneous rocks, fractured, faulted and generally complex.

The best HSA prospects in Scotland are probably in Devonian sedimentary strata (roughly 420 to 360 million years old) underlying the northern part of the Midland Valley and the southern onshore margin of the Moray Firth Basin, and in Permo-Triassic strata (roughly 300 to 200 million years old) filling small geological basins in parts of south-west Scotland. It is emphasised, however, that current understanding of the distribution and properties of aquifers in Scotland comes very largely from surface and near-surface observations, and we know relatively little about aquifer distributions and properties at depth. The ability of water to move through rocks can change significantly with depth, and testing in deep boreholes will be required to gauge the suitability at depth of any setting with HSA potential.

Relatively high temperatures at the bottom of some coastal boreholes suggest that hot water from offshore sedimentary aquifers may have migrated locally to shallower levels in onshore margins of the aquifers. It may prove possible in some places to access HSA prospects in offshore (near-shore) sedimentary basins by drilling inclined boreholes from onshore coastal locations.

Recommendations

R6 More detailed investigation of parts of the Midland Valley to identify specific targets with HSA potential.

R7 Further investigation of possible thermal anomalies in some onshore margins of large offshore basins such as the Moray and Solway firths and the Firth of Clyde.

R8 Testing in deep boreholes to gauge the actual permeability and overall productivity at depth in settings with HSA potential.

Hot dry rocks

In Hot Dry Rock (HDR) resources, heat is extracted from ‗dry‘ crystalline rocks by fracturing them, injecting cool water into the hot fractured rock, and extracting the resulting hot water. This requires the development of an Enhanced (or Engineered) Geothermal System (EGS). The EGS concept typically involves developing a ‗loop‘ in the hot rock consisting of boreholes at either end of a network of connected, open fractures, through which cold water is introduced and hot water is removed. HDR resources typically yield hotter water (100–200°C) than HSA resources, and the thermal energy stored therein is converted into electricity at the surface.

HDR projects are currently being developed in several parts of the world, including Australia, France, and the USA. Some of these have the potential to yield substantial amounts of energy but as yet none is being operated on a sustainable, commercial basis. Two projects to exploit HDR prospects are currently being developed in the UK, both in the granite intrusions of Cornwall: the United Downs Project and the Eden Deep Geothermal Energy Project.

HDR resources typically will be deeper and hotter than Hot Sedimentary Aquifer (HSA) resources. Consequently, they have the potential to produce electrical power, but they will probably present a greater technical challenge than HSA resources. In recent years the development of binary cycle power plants, in which electricity can be generated using water that is cooler than 100ºC, has greatly improved the potential for recovering geothermal energy from HDR prospects that previously would have been considered marginal or not viable.

The 'regional geothermal gradient' for Scotland (see The heat resource in Scotland, above) suggests a temperature of 150°C would be reached at a depth of approximately 4,000 metres, which is within the widely quoted practical lower limit for exploiting HDR resources (5,000 metres). If the more conservative geothermal gradient suggested by borehole temperature data from onshore boreholes is used (30.5°C/km) then 150°C should be encountered at approximately 4,900 metres, still within the 'accessible zone'. However, the lack of temperature data for crystalline rocks in deep (> 2 km) onshore boreholes means that caution should be exercised in applying the regional temperature gradient to potential HDR settings.

The best HDR prospects in Scotland are likely to exist in geological settings where heat produced by radioactive decay of elements like uranium (radiogenic heat) in the crust augments the background heat flow, producing localised thermal anomalies. There are numerous exposed granite intrusions in Scotland, and a small proportion of these produce significant quantities of radiogenic heat. These 'High Heat Production' (HHP) granites occur mainly in the East Grampians region, and two crop out to the north of Inverness. A previous investigation of the HDR potential of the East Grampians HHP granites reported disappointingly low heat flow values, but this work predated the research described above showing that heat flow values in Scotland probably underestimate the size of the heat resource beneath the climate-affected zone. The possibility remains, therefore, that some of the exposed HHP granite intrusions in Scotland have HDR potential.

Granite intrusions can be buried beneath a thick cover of younger sedimentary rocks. Where HHP granite intrusions have been buried in this way, some of the heat passing through and generated within the granite may become trapped beneath the sedimentary rocks, particularly if they are poor heat conductors. Over geological time, large reservoirs of trapped heat can potentially develop in this way. Based mainly on geophysical evidence, buried granite intrusions are inferred to exist in Caithness, beneath the East Grampians region, and in south-east Scotland, but to date no buried intrusions of HHP granite have been proved in Scotland. Based on the distribution of HHP granite at outcrop, intrusions of HHP granite sitting beneath thick piles of sedimentary rock may exist beneath the Moray Firth and its onshore fringes.

The evidence base for assessing the potential for Hot Dry Rock prospects in Scotland is far from adequate. Most significantly, we need to improve our understanding of the distribution in Scotland of exposed and buried intrusions containing HHP granite.

Recommendations

R9 Compile heat production data for all the granite intrusions of Scotland to identify all intrusions that have HHP character at outcrop.

R10 Conduct research to identify whether some of the exposed intrusions that do not have HHP character would have had HHP character in now-eroded portions, or may have HHP character in still-buried portions.

R11 In offshore areas, use seismic survey data and information from wells to identify buried intrusions and intrusions exposed on the sea floor.

R12 In onshore areas, re-interpret existing regional geophysical data and 3D geological models using modern methodologies and up-to-date knowledge of the surface and subsurface geology to identify possible buried granite intrusions (and other potential HDR settings).

R13 Characterise the fracture network in exposed HHP intrusions.

R14 Conduct a programme of deep drilling to provide measured and observed, factual data from within the deep geothermal regime; to penetrate beyond the influence of surface- and near-surface effects on the geothermal gradient, a deep geothermal borehole would probably need to extend to a depth of at least 3 kilometres, and ideally to 5 kilometres.

1 Introduction

This report contains the British Geological Survey (BGS) contribution to a collaborative project between AECOM and BGS to produce a qualitative assessment of deep geothermal energy potential in Scotland for the Scottish Government (Scottish Government Contract Ref. AEC/001/11) Study into the Potential for Deep Geothermal Energy in Scotland). BGS was asked to provide the Stage One deliverable —Identifying and assessing geothermal energy potential”, comprising an assessment of areas in onshore Scotland most likely to hold deep geothermal resources based on existing geological and geothermal data sets. AECOM undertook the Stage 2 deliverable —Development of Key Policy Options” in which policy options and key actions are identified that the Scottish Government can potentially implement to encourage commercial exploitation of the available geothermal resource.

The geological assessment (Stage One) presented here is limited to onshore parts of Scotland and to depths exceeding 100 metres below ground surface (defined as ‗deep‘ in the project brief). No new measured data have been obtained for the project; the assessment is based on secondary sources of information (published data and data held by BGS). Data from offshore wells have been used to inform the assessment of the onshore geothermal resource, but offshore geothermal energy potential has not been assessed. The objective of Stage One, and this report, is to provide the Scottish Government with a qualitative assessment of the deep geothermal resource in Scotland, with supporting maps and models. The meaning of geological and technical terms is explained where appropriate in the text, and a glossary is provided.

The specific objectives of Stage One were framed as three tasks in the project brief:

- Task 1 - Identify and map areas most suitable for further investigation of deep geothermal energy potential.
- Task 2 - Collate all available data on the surface and subsurface rocks into a three dimensional model of structure and thermal patterns through the top few kilometres of Scotland‘s continental crust.
- Task 3 - Predict areas most likely to hold deep geothermal resource, to target for more detailed investigation.

For Task 2, a 3D model of abandoned mine working in the Midland Valley of Scotland has been built. However, it has been concluded that building a complete 3D model of thermal patterns in Scotland‘s continental crust would not benefit this study (see introduction to Part 2).

The report is divided into two parts: Part 1 contains background information relating to geothermal energy (section 2) and the geology of Scotland (section 3), and a review of existing geothermal data for Scotland (section 4); Part 2 contains an assessment of geothermal energy potential in three categories of potential resource that were specified t in the project brief: mine water, Hot Sedimentary Aquifer (HSA), and Hot Dry Rock (HDR).

The geothermal energy potential in Scotland was first investigated in detail in the late 1970s and early 1980s as part of the project —Investigation of the geothermal potential of the UK”, funded by the then Department of Energy, and the European Union. In Scotland, the project focused mainly on the HDR potential of granite intrusions in the East Grampians region. The approach and outcomes of the project are reviewed in more detail in section 8.2 of this report. The conclusions were generally discouraging from a Scottish perspective, and several decades passed subsequently with little interest in the subject and virtually no new research.

In recent years, the potential for exploiting ‗deep‘ geothermal energy in Scotland has been the subject of renewed interest, perhaps most notably in the form of several online articles by Professor Ed Stephens of St Andrews University (A growing number of publications includes two recent reports by engineering consultants Sinclair Knight Merz; these reports contain reviews of the geothermal resource in Scotland (Sinclair Knight Merz, 2012a,b).

Part 1

Background, context and existing data

2 Background to geothermal energy

2.1 SOURCES OF HEAT, HEAT MEASUREMENT AND FACTORS AFFECTING HEAT TRANSFER

2.1.1 Sources of heat

The heat resource that exists at accessible depths within Earth‘s crust is derived from a number of sources, but three dominate:

(i) Stored heat in Earth‘s core and mantle, which dissipates by various means into the crust. The amount of heat supplied to the base of the crust from the mantle is related to the thickness of the lithosphere (the top part of the mantle), which can vary significantly, and the time elapsed since the last geological event to cause a significant transfer of heat across the mantle-crust boundary (Polyak and Smirnoff, 1968; Chapman and Pollack, 1975; Sclater et al., 1980).

(ii) Heat generated by the motion and interaction of tectonic plates. This contribution, which commonly manifests at Earth‘s surface as volcanic activity, will be small to non-existent in regions of the crust that have been stable for a long time (this includes Scotland).

(iii) Heat generated by the radioactive decay of naturally occurring elements (radiogenic heat). Virtually all rocks contain small quantities of elements that undergo radioactive decay, which generates heat in situ. The quantity of heat that can be produced by a rock in this way is referred to as its heat production (HP) capacity.

2.1.2 Heat production capacity

Many of the elements that undergo radioactive decay have over geological time become concentrated in the upper parts of the crust, with the consequence that the HP capacity of upper crustal rocks is generally substantially higher than it is for rocks in the lower crust and the mantle. The chemical elements potassium (K), uranium (U) and thorium (Th) are generally the most abundant sources of radiogenic heat in continental crust. The HP capacity of a rock can be calculated from analysis of its chemical constituents, using the equation:

$A = 0.1326\rho(0.718U + 0.193Th + 0.262K)$ (e.g. Manning et al., 2007)

where A is heat production in $\mu W\ m^{-3}$, ρ is rock density in $g\ cm^{-3}$, U is uranium content in $mg\ kg^{1}$

(also expressed as ‗parts per million‘, or ppm), Th is thorium content in $mg\ kg^{-1}$ (ppm), and K is potassium content in weight % K_2O. Other forms of this equation, such as

$A = 10^{-5}\rho(9.52U + 2.56Th + 3.48K)$ (Rybach, 1988)

are used widely and produce the same result (but note that in this case ρ is expressed in kg m^{-3}).

HP capacity can also be determined indirectly from well logs (spectral gamma-ray log or integrated gamma-ray spectrum) using the empirical (linear) relationship between heat production and gamma ray readings that has been shown to exist for a wide range of lithologies (Bücker and Rybach, 1996).

Potassium, uranium and thorium concentrate in the chemically evolved parts of silica-rich magmas, so granite intrusions commonly contain high (and in some cases anomalously high) concentrations of these elements relative to other lithologies. Granite intrusions with unusually high HP values are referred to as high heat production (HHP) granites. There is no widely accepted HP threshold for distinguishing rocks with HHP character, but the term is usually used when HP values exceed 4 μW m^{-3}. For the purposes of this report, rocks with HP values ≥ 4μWm^{-3} are considered to have HHP character. A granite intrusion containing 4% potassium (as K_2O), 20 parts per million (ppm) uranium and 40 ppm thorium would, assuming a typical density for granite of 2.63 g cm^{-3}, generate around 8 μW of heat per cubic metre of rock per second, and hence be classed as HHP. This is a small amount of heat, but granite intrusions typically contain many billions of cubic metres of rock, and the heat may be generated continuously for many millions of years. Extracting the thermal energy stored in one cubic kilometre of hot granite such that its temperature drops from 240ºC to 140ºC would reportedly yield the energy equivalent of 40 million barrels of oil (statistic taken from the website of Geodynamics Ltd; www.geodynamics.com.au). Rocks other than granite can have HHP character, but they generally don‘t occur in volumes large enough to have geothermal energy potential.

2.1.3 Heat flow

The various sources of naturally occurring heat contribute collectively to heat flow, which can be defined generally as the movement (or transfer) of heat through the Earth. Heat flow is also the standard measure of the amount of heat travelling through Earth‘s crust, and is expressed most simply as:

$q = k\beta$

where q is heat flow in mW m^{-2}, k is the thermal conductivity of the rock (in W m^{-1} K^{-1}) and β is the vertical temperature gradient (in ºC per kilometre). Thermal conductivity measures the ability of a material (such as a type of rock) to conduct heat, in this case expressed as a unit amount of heat (one degree Kelvin) measured in watts per second per vertical metre. The vertical temperature gradient, which can be thought of as _the rate of temperature increase in the Earth with depth‘, is also referred to as the geothermal gradient. Geothermal gradient is usually calculated by measuring the temperature at two different depths in a borehole.

On average, heat flow from the mantle in continental areas is around 20 mW m^{-2}, while the mean heat flow across all continents is 65 mW m^{-2} (Turcotte and Schubert, 2002); the difference is due mainly to the contribution of radiogenic heat in crustal rocks. The average geothermal gradient in continental areas is 25–30ºC/km.

2.1.4 Factors affecting the supply and transfer of heat in the crust

Heat flow is assumed to be essentially the same at all points within a vertical column of the Earth‘s crust if the heat supply is constant and heat transfer is conductive and vertical. Thus, a constant heat flow is theoretically maintained throughout a vertical column of rock spanning any depth range and including multiple rock types, because changes in thermal conductivity (due to changing rock type, permeability, pressure and temperature) are associated with coincident, proportionate changes in geothermal gradient. Put another way, any increase in thermal conductivity is matched by a proportionate decrease in geothermal gradient, and vice versa. This situation should ensure that the heat flow below any point on Earth‘s surface is constant, and therefore that heat flow measurements (which are made in the near-surface zone) should provide a good indication of the size of the heat resource at depth. However, several factors (described briefly below) can affect the supply of heat and how it is transferred, particularly in shallow parts of the crust. These factors reduce the degree to which near-surface measurements of heat flow can be considered a reliable basis for estimating temperatures and the size of the heat resource in deeper parts of the crust.

Local sources of heat

Although the supply of ‗background‘ or ‗stored‘ heat (derived from the mantle) may be broadly constant at any point in the crust at any given time, the supply of radiogenic heat can vary significantly on a local, and sometimes regional, scale. Granite intrusions in particular can contain elevated concentrations of radiogenic elements and so can be a source of thermal anomalies in the crust. Where such intrusions crop out at the surface or are concealed in the near-surface zone, near-surface heat flow may be significantly higher than background heat flow. Such intrusions are potentially important sources of geothermal energy in Scotland, and are described in more detail in section 8.2.

Topography

Topographic relief can perturb heat flow, so heat flow values calculated in the near-surface zone of hilly areas require a correction. Measured heat flow will typically be greater in valley floors than on the tops of hills. Corrections for topography are typically based on the method of Bullard (1940). Topographic corrections to heat flow data gathered from four granite intrusions in the East Grampians region of Scotland (see section 8.2) involved downward corrections of the uncorrected values of between 3.7% (borehole sited on a hillside) and 10.5% (borehole sited on a valley floor) (Wheildon et al., 1984).

Changes in surface temperature due to geologically recent climate change

The geothermal gradient is controlled primarily by heat generated within the Earth. However, the temperature at Earth‘s surface ‗pins‘ one end of the geothermal gradient curve, and changes in surface temperature due to climate change must therefore cause transient changes to the near-surface part of this curve. In the last two million years, Earth has been subjected to a number of cooling-warming cycles (the ‗Ice Age‘), with areas in higher latitudes (including Scotland) affected most by extreme temperature fluctuations.

Within the last decade, a strong body of evidence has emerged showing that transient changes in surface temperature are recorded in subsurface temperature gradients. For example, a study of heat flow measurements from more than 2,000 boreholes in northern Europe and North America revealed a systematic increase in heat flow with depth, and indicated that heat flow values determined from boreholes less than 2 km deep could be underestimated by up to 60% (Gosnold et al. 2011). Other authors (e.g. Popov et al. 1998; Szewczyk and Gientka, 2009) have described the same effect.

Scotland was strongly affected by the Ice Age glaciations, so warming of the atmosphere since the last prolonged glacial period is likely to have perturbed the top part of the geothermal gradient. Heat flow measurements in shallow boreholes therefore probably underestimate the actual background ‗steady-state‘ heat flow that is assumed to exist beneath the climate-affected zone. Unpublished work by BGS (J P Busby pers. comm.), in which an estimated model of the surface temperature dating back 160 000 years was applied to the East Grampians region of Scotland, indicates that recent changes in the climate may have suppressed near-surface heat flow in the region by up to 29%.

Inefficient heat transfer through low conductivity rocks (trapped heat)

At the Cooper Basin geothermal energy prospect in Australia (e.g. Chopra and Wyborn, 2003), a deep borehole has revealed an unusually high temperature in a buried granite intrusion (240ºC at 3.7 km). The high temperature has been ascribed to a combination of the HHP character of the granite and the low thermal conductivity of the sedimentary rocks that overlie the granite. In other words, a reservoir of temporarily trapped heat seems to have developed in the granite because heat transfer through the overlying rocks is too inefficient to keep up with the supply of heat. Heat flow measured above such a setting may therefore underestimate the size of the (trapped) heat reservoir at depth.

Heat refraction

Some bedrock geology configurations, including inclined strata, can cause heat refraction such that conductive heat transfer deviates from vertical.

Convective heat transfer

Heat transfer through the crust occurs primarily by conduction, but heat transfer by convection in water, liquid hydrocarbon and magma, can play an important role in some parts of the crust. Heat can theoretically be transported in any direction by this process. Shallow parts of the crust can contain substantial amounts of water, and convective heat transfer is therefore likely to be important in rocks with high permeability.

2.2 CLASSIFICATION AND EXPLOITATION OF GEOTHERMAL RESOURCES

2.2.1 Classification based on temperature of heat resource

Low enthalpy (low temperature) resources provide warm water that can be used for direct applications. Low enthalpy resources can be divided into two types. (i) Indirect use resources exploit relatively cool water (~8–15ºC) in the shallow sub-surface (<c.200 m depth). The low energy heat of indirect use resources is collected with a ground source heat pump either with ground collector loops in trenches or boreholes, or from water in shallow, permeable formations. Ground source heat pumps can be installed at most locations, but the design of each system depends on local ground conditions. (ii) Direct use resources comprise water that can be pumped directly from underground and used immediately for heating; these resources are generally in the temperature range 20–80º C and in the UK are found within permeable rocks in the depth range 0.5–4 km.

High enthalpy (high temperature) resources yield hot water capable of driving turbines and generating electricity. The concept underlying the exploitation of high-enthalpy resources is simple: sink one or more boreholes into an accessible zone of hot rocks, extract the thermal energy in the form of hot water/steam, and use this to generate electricity at the surface. In parts of the world where there is active or recent volcanism, hot water circulates at shallow depths in highly permeable fracture systems where it can be exploited directly and relatively easily. Electricity is generated directly from these conventional ‗hydrothermal‘ systems in Iceland, Japan, parts of continental Europe, western USA and a few other parts of the world, but they are globally rare. More usually, the permeability and/or fluid content of a hot rock mass needs to be enhanced artificially in order to extract the geothermal energy in commercially viable quantities. Concepts and projects requiring the use of advanced technology to recover a high-enthalpy geothermal resource are known as Enhanced (or Engineered) Geothermal Systems (EGS).

Some heat is lost in the process of transferring it from the extraction zone to the power-generating facility, so the minimum target temperature for a deep geothermal resource capable of generating electricity economically using conventional (steam-driven) turbine technology is commonly stated to be around 150 ºC; however, an operation capable of generating a substantial power output over a period of decades using conventional power-generating technology may require an even hotter resource, perhaps in the region of 200ºC. In parts of the continental crust exhibiting the average geothermal gradient of 25–30ºC/km, this temperature would be encountered at a depth of approximately 7 km, assuming a mean annual surface temperature of around 10ºC. Modern drilling technology is capable of reaching depths in excess of 10 km; however, the technical challenges and associated cost of drilling rise steeply with increasing depth. The economic viability of an EGS prospect therefore depends critically on minimising the depth to target temperature. Most concepts and established experimental facilities for EGS are based on a target depth range of 4 to 5 km. A consistent (‗steady-state‘) geothermal gradient of between 38 and 48ºC/km would be required to achieve a temperature of 200ºC within that depth range.

In recent years, the development of binary cycle power plants has greatly improved the potential for recovering geothermal energy from prospects that previously would have been considered marginal or not viable. A heat exchange system at the power plant is used to transfer thermal energy from hot water into a second liquid, usually a butane or pentane hydrocarbon liquid, which has a lower boiling point than water. Vaporisation of the second liquid drives the turbines, hence electricity can be generated using water that is cooler than 100ºC. The range of water temperatures that can be used in binary cycle power plants extends down to less than 40ºC. However, the efficiency of such systems decreases significantly with decreasing temperature, and a commercially viable EGS utilising a deep geothermal resource and binary cycle power plant technology is likely to require water of a temperature significantly above the lower limit at which it is possible to generate electricity.

2.2.2 Classification based on setting of heat resource

Geothermal resources can also be classified according to the setting in which the heat resource resides. Sinclair Knight Merz (2012a) defined two main geological settings:

- hydrothermal systems where the heat resource is contained within a water aquifer, e.g. abandoned mine workings and hot sedimentary aquifers;
- petrothermal systems where the heat is contained in the rocks, e.g. hot dry rocks.

Abandoned mine workings (mine water)

Mine water in abandoned workings in Scotland‘s Midland Valley might form an important low enthalpy resource for space and domestic hot water heating, and related uses. Mining creates ―anthropogenically enhanced aquifers” (Banks, 1997) with additional permeability within strata that otherwise typically have significantly lower permeability. Mine waters are exploited using GSHP technology. Mine workings often spanned a significant depth range (up to several hundred metres), enabling water to be abstracted from one depth interval and returned to the ground at a different depth. This vertical separation can increase the time before the returned water, at lower temperature, starts to arrive at the point of abstraction (thermal breakthrough), which can improve the efficiency of a scheme. Mines can extend to relatively deep levels, so in some cases they can provide easy access (e.g. via remnant shafts) to higher temperature water. For example, a borehole at the Solsgirth Colliery in Clackmannanshire recorded at temperature of 21.5°C at a depth of 387 metres.

Hot sedimentary aquifers

In the Hot Sedimentary Aquifer (HSA) concept, the heat energy is contained in permeable, water-bearing sedimentary rocks (aquifers), and is recovered by simply sinking one or more boreholes into the resource and extracting the hot water. Although the aquifer water holds a substantial amount of heat, the main heat store resides in the host rocks, and water drawn into the aquifer to replace that drawn out via a borehole will absorb heat from the host rocks. The best HSA prospects will exist where a natural system of circulating groundwater yields a high and sustainable flow rate of heated water.

Hot dry rocks

Much of the world‘s accessible high-enthalpy geothermal energy exists in crystalline (non-porous) rock at depths exceeding several kilometres. Such rocks are generally assumed to lack open fractures and consequently have very low permeability. They are therefore essentially dry, hence they are known as Hot Dry Rock (HDR) resources (e.g. Batchelor, 1982; Lee, 1986). The EGS concept for exploiting HDR resources relies on creating open fractures to hydraulically connect two or more boreholes drilled some distance apart into a hot rock zone. Cold water pumped down one or more ‗injection‘ wells flows through the fracture system, absorbing as it does the geothermal energy held in the enclosing rocks, and is recovered as hot water from one or more production wells (Figure 1). The thermal energy stored in the water can be converted into electricity at the surface in various ways.

Hydraulic fracturing (injecting water at high pressure through a borehole to open existing fractures and/or create new ones in deeply buried rock) is used to develop the system of open fractures – a process usually referred to as stimulation. The fracture walls then act as heat exchange surfaces, and an engineered geothermal reservoir is created as cold water is pumped into the system. The position, shape and volume of the developing reservoir is monitored using micro-seismic survey techniques, which locate the origins of the seismicity induced as fractures open during hydraulic fracturing. In operational mode, water is pumped through the injection well under high pressure, which keeps the fractures open and forces the water to circulate through the system in a closed loop, arriving in the form of hot water (or steam) at a power plant on the surface. The same water, relieved of its heat, can then be re-cycled back into the injection well.

In recent years, major projects in Australia, France and the US have demonstrated the considerable potential for generating electricity using EGS to exploit HDR resources. All of these projects have exploited the same particularly favourable geological setting, where a thick layer of sedimentary rocks overlies an intrusion of granite with elevated concentrations of radioactive elements. The sedimentary rocks act like a thermal blanket, trapping beneath them the heat generated in the granite, which builds up over millions of years into a substantial geothermal resource at a relatively shallow, and therefore accessible, depth (~4–6 km). The potential for ‗buried hot granite‘ resources to exist in Scotland is assessed in section 8.2.4.

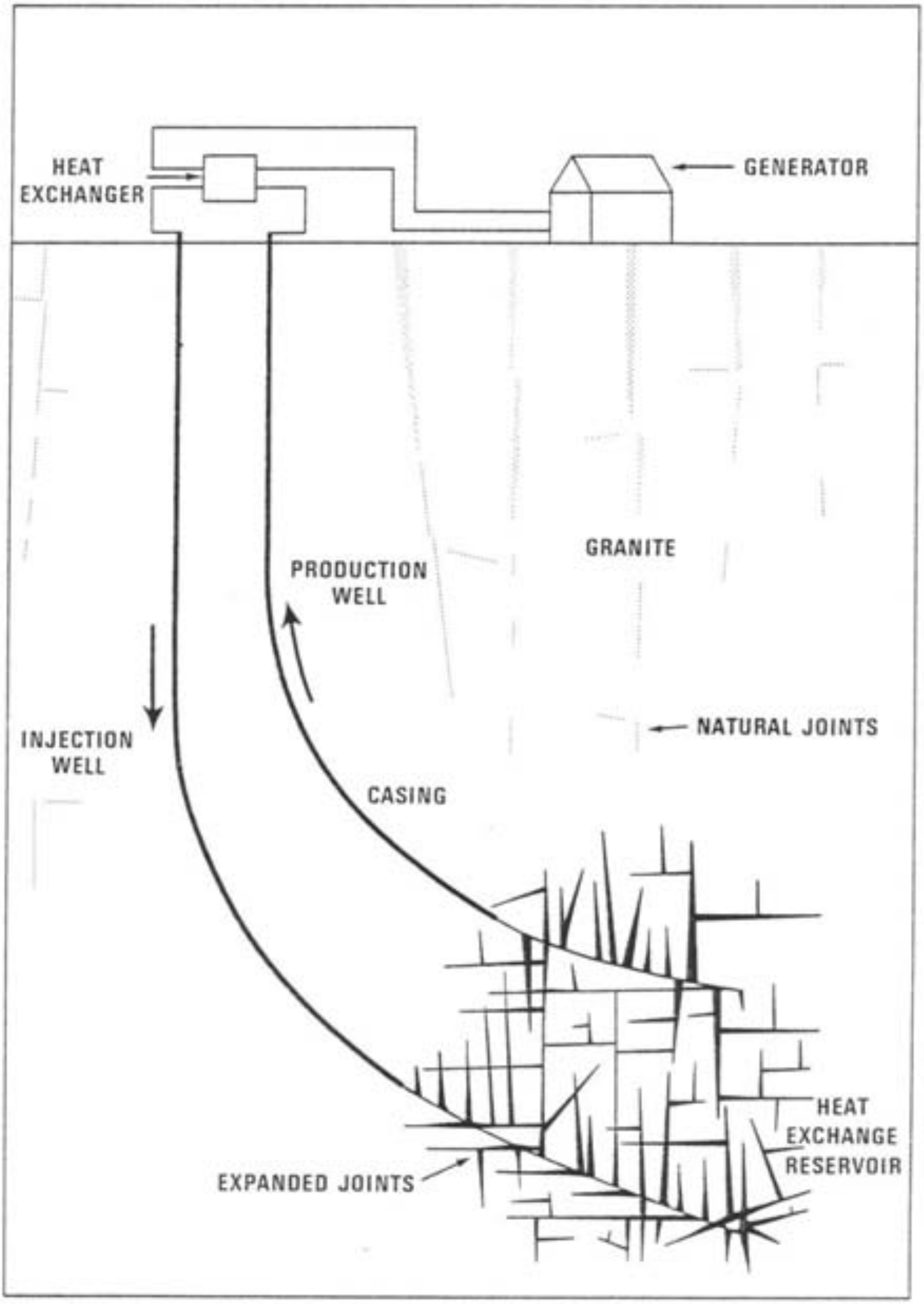


Figure 1 Diagram from Lee et al. (1984; Figure 1.1) illustrating the ―classic" concept of a two-well hot dry rock system. Note that in this representation the HHP granite extends from the reservoir to the ground surface, i.e. it is not buried beneath a layer of low thermal conductivity rocks.

3 The geological context

3.1 SOME TERMINOLOGY AND CONCEPTS

This section contains a brief introduction to some of the geological terminology and concepts that are relevant to this assessment of geothermal energy potential. The glossary also contains definitions for some terms.

The Earth has a core, a mantle, and a crust which form approximately 15%, 84% and less than 0.1% respectively of its volume. The crust is effectively the thin ‗skin‘ of cool, solid, brittle rocks forming the outermost layer or shell of the Earth. In the continents the crust is typically approximately 30 km thick, but it can be significantly thicker where two continents have collided. Beneath the oceans, the crust is substantially thinner, typically just 5–10 km thick. The deepest borehole drilled anywhere in the world to date, on the Kola Peninsula in Russia, reached a maximum depth of 12.26 km. For comparison, most of the boreholes that have so far been drilled in onshore parts of Scotland are less than 1 km deep, and most boreholes drilled offshore in the hunt for hydrocarbons do not exceed 5 km.

The crust consists of three main classes of rocks:

- igneous rocks form by solidification of magma (molten rock); they can solidify within the crust (forming intrusions) or they can erupt onto Earth‘s surface (forming lava flows and pyroclastic deposits); common types of igneous rock include granite and gabbro (which always occur as intrusions), and basalt and andesite (which are commonly erupted, but can form intrusions).
- sedimentary rocks form by deposition of particulate matter at Earth‘s surface; common types of sedimentary rock include sandstone, conglomerate, siltstone and limestone.
- metamorphic rocks are former igneous rocks or sedimentary rocks that have been subjected to heat and pressure within Earth‘s crust, with the result that the original textures and mineral assemblages have changed significantly. Common types of strongly metamorphosed rock include gneiss and schist.

Rocks can be either crystalline (formed entirely of interlocking crystals) or granular (formed of adhering particulate matter, such as sand grains). Metamorphic rocks and most igneous rocks are crystalline. Most sedimentary rocks are granular.

Most rocks are brittle, and when they are subjected to strain they react by breaking along fractures. There are two common types of fracture: joints, which are cracks formed by simple opening; and faults, which develop when the rock breaks under shearing strain and the opposing sides of the break move relative to each other and parallel to the fracture.

Fluids (including water, oil, natural gas and air) pass through rocks in pore spaces. There are two main types of pore space: fracture pore space, in which fluid is held within fractures; and intergranular (or matrix) pore space, in which fluid is held within the spaces between grains or particles. Water can only move through crystalline rocks via connected open fractures, whereas in granular rocks water can move through intergranular pores, or through fractures, or a combination of both.

The position of rocks within the crust can change significantly over geological time. On a continental scale, this happens as tectonic plates move on top of the mantle. On a smaller scale, movements on geological faults cause rocks to change their positions relative to each other. Rocks also move vertically within the crust: those that were formerly at Earth‘s surface can become buried beneath younger deposits, and rocks that were originally at considerable depth can rise to shallow depths as a result of uplift and erosion. In this way, rocks that formed at Earth‘s surface become buried and metamorphosed, and rocks that formed or were modified deep in the crust can become exposed at Earth‘s surface.

In many parts of the crust, older rocks that were formed or affected by one set of events are overlain by younger rocks that were formed or affected by a different set of events. In such settings, the older rocks are referred to as basement and the younger, overlying rocks, as cover. Typically, the cover will consist of non-metamorphosed sedimentary (granular) rocks, and the basement will be metamorphosed (crystalline) rocks. Basement-cover relationships are potentially important in geothermal energy, as rock units with contrasting characteristics (e.g. permeability, heat production capacity and thermal conductivity) can be juxtaposed across the boundary.

Thermal conductivity varies from rock type to rock type. Typical values reported for some common rock types are presented in Table 1. However, the thermal conductivity of rock can change with changing temperature and pressure. For example, compaction (which increases with depth and results in loss of pore space) can increase thermal conductivity. This has little effect in crystalline rocks such as granite (which typically has a very low proportion of pore space at all depths) but can make a significant difference in rocks that are typically porous at shallow depths, like sandstone. The thermal conductivity of rocks also typically decreases slightly with increasing temperature. Thermal conductivity values are usually reported for rocks at the surface, or in the near-surface zone, but it must be borne in mind that for some rock types thermal conductivity is likely to change significantly with depth.

Rock type	**Rock character**	**Mean thermal conductivity** (W m^{-1} K^{-1})	**Reported in**
sandstone	sedimentary	3.3 to 4.9	Lee et al., 1984
mudstone	sedimentary	1.5 to 2.2	Lee et al., 1984
limestone	sedimentary	2.8 to 3.0	Lee et al., 1984
coal	sedimentary	0.31	Lee et al., 1984
slate (metamudstone)	metamorphic	2.7	Lee et al., 1984
basement metasediment	metamorphic	3.51	Lee et al., 1984
basement metasediment	metamorphic	3.1 to 3.5	Wheildon et al., 1984
granite	igneous, silica-rich	3.0 to 3.5	Wheildon et al., 1984
granodiorite & tonalite	igneous, silica-rich	2.5 to 2.9	Wheildon et al., 1984
dolerite (and basalt)	igneous, silica-poor	2.2	Lee et al., 1984
peridotite	igneous, silica-poor	2.2	Wheildon et al., 1984

Table 1 Thermal conductivity values reported for common rock types.

3.2 BEDROCK GEOLOGY OF SCOTLAND

Scotland has a complex and diverse bedrock geology, which is the product of more than three billion years of Earth processes (Figure 2). The country sits on the edge of the European continent and has been geologically ‗quiet‘ for more than 50 million years; there is no evidence at the surface or in explored parts of the subsurface for ongoing volcanic or hydrothermal activity.

For the purposes of this assessment of geothermal energy potential, the numerous units that make up the bedrock geology of the country have been simplified into seven ‗categories‘, each of which has a distinct character in terms of component rocks, permeability and thermal conductivity (Figure 3 and Table 2).

3.2.1 Strongly metamorphosed igneous and sedimentary rocks

The Western Isles and Northwest Highlands are underlain mainly by thickly banded, strongly metamorphosed, crystalline rocks (gneiss), much of which consisted originally of intrusions of granitic (granite and similar) and basaltic (basalt and similar) rock. These are the oldest rocks in Scotland, and rocks with similar characteristics probably occur at depth beneath most (possibly all) other parts of the country. Sequences of non-metamorphosed sandstone and metamorphosed sandstone and limestone overlie the gneisses in parts of the mainland. The area is bounded to the east by the outcrop of the Moine Thrust Zone, a major fault which dips east at a low angle and therefore underlies a large area of ground to the east of its position at surface.

3.2.2 Metamorphosed sedimentary rocks

Much of the Shetland Islands and most of the Northern Highlands and Grampian Highlands are underlain by metamorphosed and folded sedimentary rocks. These originally formed a very thick sequence of interbedded sandstone and mudstone units, but metamorphism has given these rocks a crystalline character. A major fault, the Great Glen Fault, separates the Northern Highlands from the Grampian Highlands. The fault is near-vertical and associated with a substantial topographic feature (the Great Glen). The Great Glen Fault may extend to the base of the crust, and possibly into the top part of the mantle. The large mainland outcrop of this category of rocks is bounded to the north-west by the Moine Thrust Zone and to the south-east by the Highland Boundary Fault. The orientation of the latter structure is not well understood, but it is likely to dip towards the north-west.

3.2.3 Weakly metamorphosed sedimentary rocks

Much of the Southern Uplands area is underlain by weakly metamorphosed sandstone and mudstone (shale). The sandstone is typically poorly sorted (wacke), and would have been relatively impermeable prior to metamorphism. Following weak metamorphism, the original sedimentary rocks now have a partly crystalline character. The originally gently dipping beds of sedimentary rock have been much disrupted by folding, faulting and tilting. The area is bounded on its north-west side by the Southern Upland Fault. The border with England defines part of the south-east boundary.

3.2.4 Large intrusions of basic igneous rock

Several large intrusions of silica-poor (basic) igneous rock (gabbro and peridotite) crop out in Aberdeenshire, including the Morvern-Cabrach, Huntly-Knock and Insch masses. The intrusions are thought to be broadly flat-lying and saucer-shaped (laccoliths).

3.2.5 Intrusions of granite and related rocks

Intrusions of igneous rock are common in many parts of Scotland. The intrusions span a wide range of compositions, including silica-rich (granite, granodiorite, tonalite), silica-poor (gabbro and peridotite), and intermediate (diorite, syenite) variants. Many thousands of small intrusions (‗minor intrusions‘) typically have sheet-like and pipe-like forms. Smaller numbers of large intrusions typically have broadly oval form at outcrop; the largest can be 30 km across and crop out over an area in excess of 300 km^2. The largest intrusions typically consist of granite and/or granodiorite (which is closely related to granite). The Grampian Highlands, in particular the East Grampians region and Argyll, contains the greatest concentration of intrusions, large and small. Concentrations of large intrusions also occur in the Northern Highlands, and the western part of the Southern Uplands. Large granite intrusions also crop out on Arran, Skye and the Shetland Islands. The Midland Valley has only a handful of relatively small granite intrusions at outcrop but is dissected by numerous minor intrusions, mainly of basaltic and andesitic composition. The granitic intrusions of Scotland are described in more detail in section 8.2.1

3.2.6 Thick and extensive lava flows

Thick sequences of mainly basaltic (silica-poor) and andesitic (intermediate silica content) lava underlie several parts of Scotland. In the Lorne area of Argyll a pile of lava flows crops out across an area of approximately 300 km^2 and has a maximum preserved thickness of c. 800 metres. In the Midland Valley, sequences of lava (and pyroclastic rocks) up to several kilometres thick underlie nearly all of the upland areas. Andesitic lavas crop out across an area of around 600 km^2 around Cheviot, astride the Scotland-England border, and have a preserved thickness of about 500 metres. Extensive fields of basaltic and andesitic lava on Skye, Mull, and in Morvern may attain a vertical thickness in excess of two thousand metres.

3.2.7 Non-metamorphosed sedimentary rocks

Thick sequences of sedimentary rock that have never been metamorphosed to any significant degree underlie large parts of Scotland, including most of the Midland Valley, the Orkney Islands, Caithness and fringes of the Moray Firth to the north and east of Inverness.

In geological terms, the Midland Valley is a fault-bounded block of relatively young, non-metamorphosed rocks that has been downthrown relative to the blocks of older, metamorphosed rocks on either side (forming the Grampian Highlands and Southern Uplands). At outcrop, the area consists very largely of sedimentary rocks and lavas of Devonian and Carboniferous age. The Carboniferous strata of the Midland Valley include the only significant occurrences of coal in Scotland. The underlying crystalline basement rocks are not exposed other than in small areas adjacent to the bounding faults, and their nature is very poorly constrained. Based on geophysical survey data, the basement-cover boundary is interpreted to be at a depth of approximately 8 km beneath much of the central part of the Midland Valley, though it is likely to be significantly shallower in places.

The Orkney Islands, Caithness and Moray Firth fringes (and the offshore areas between them) are underlain by sedimentary rocks that were deposited on the floor of, and adjacent to, a large shallow lake (the Orcadian Lake). The sedimentary succession is characterised by alternating beds of conglomerate and sandstone in some areas, and siltstone and sandstone in others.

In south-west Scotland, sedimentary rocks of mainly Permian and Triassic age are preserved in several places, filling ancient valleys and downthrown blocks. These are described in more detail in section 7.3.1.1.1.

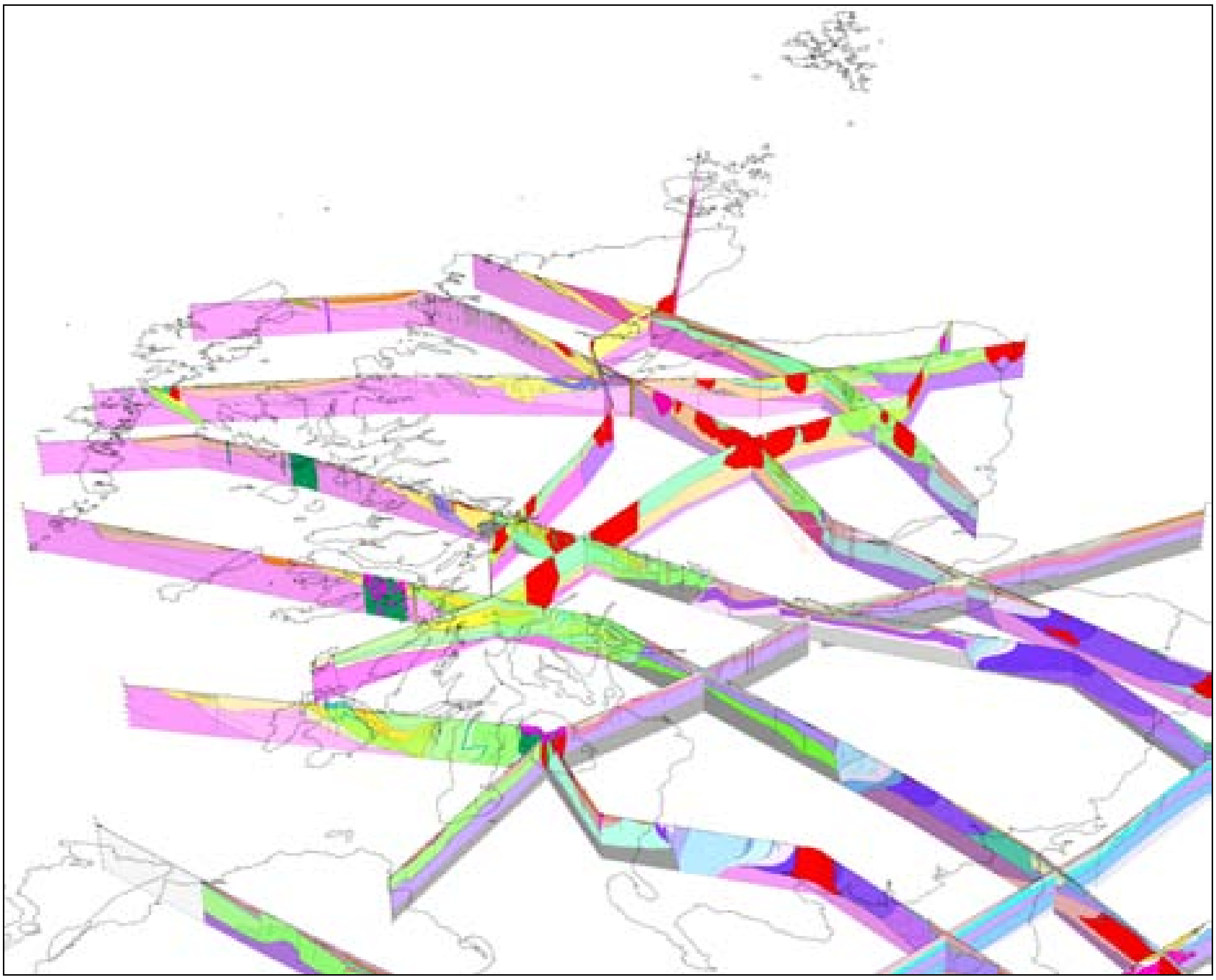


Figure 2 Cross-sections of Scotland's bedrock geology, constructed down to 15 km. The coloured polygons represent different geological units (colours are not the same as those used in Figure 3). A detailed description of the cross-sections is beyond the scope of this report, but they give a sense of the complexity of the subsurface geology.

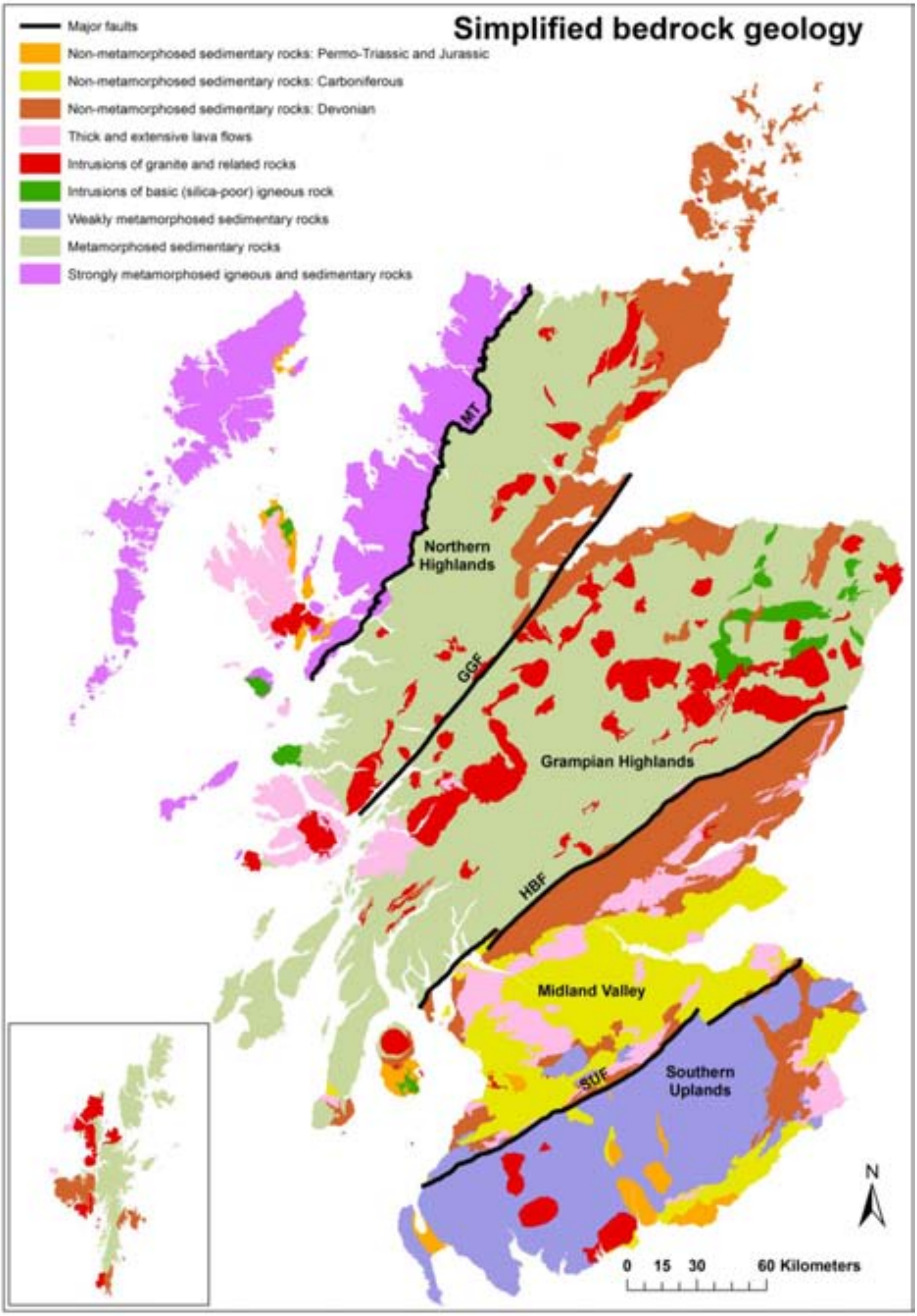


Figure 3 Simplified BGS bedrock geology map of Scotland. MT – Moine Thrust; GGF – Great Glen Fault; HBF – Highland Boundary Fault; SUF – Southern Upland Fault.

Geological category	Main geological units	Main areas of outcrop	Principal lithologies	Overall rock character	Typical permeability	Thermal conductivity *
Non-metamorphosed sedimentary rocks	Stewartry Group; Hopeman Sandstone Formation; Stornoway Formation	Morayshire; Ayrshire; Dumfries and Galloway	sandstone; conglomerate	granular	high and very high	high
	Inverclyde Group; Strathclyde Group; Clackmannan Group; Scottish Coal Measures Group	Midland Valley	sandstone; mudstone	granular	moderate	low to high
	Old Red Sandstone Supergroup	Orkney Islands; Caithness and mainland fringes of Moray Firth Basin; Midland Valley; Scottish Borders	conglomerate; sandstone	granular	low to high	high
Thick and extensive lava flows	Mull Lava Group	Mull; Morvern	basalt; tuff	crystalline	low	low
	Skye Lava Group	Skye	basaltic-rock	crystalline	low	low
	Clyde Plateau Volcanic Formation	Midland Valley (Campsie, Kilpatrick, Renfrewshire, and Gargunnock hills)	basaltic-rock; andesitic-rock; volcaniclastic-rock	crystalline	low	low to moderate
	Cheviot Volcanic Formation	Scottish Borders	andesite; rhyolitic-rock; volcaniclastic-rock	crystalline	low	moderate
	Ochil Volcanic Formation	Midland Valley (Ochil and Sidlaw hills)	basalt; andesite	crystalline	low	low to moderate
	Lorne Plateau Lavas	Argyll	andesite	crystalline	low	moderate
Intrusions of granite and related rocks	Scottish Highlands Silurian Suite	Northern Highlands; Grampian Highlands; Dumfries and Galloway	granite; granodiorite	crystalline	very low	high
Intrusions of basic igneous rock	Northeast Grampian Basic Subsuite	Aberdeenshire	gabbroic-rock; peridotite	crystalline	very low	low
Weakly metamorphosed sedimentary rocks	Leadhills Supergroup; Moffat Shale Group; Gala Group; Hawick Group	Southern Uplands	wacke sandstone; shale	crystalline	low	very low to moderate
Metamorphosed sedimentary rocks	Badenoch Group; Moine Supergroup; Dalradian Supergroup	Shetland Islands; Northern Highlands; Grampian Highlands	metamorphosed sandstone and mudstone	crystalline	very low and low	high
Strongly metamorphosed igneous and sedimentary rocks	Lewisian Complex	Western Isles; Northwest Highlands	metamorphosed igneous and sedimentary rocks	crystalline	very low and low	moderate to high

Table 2 Summary information for the seven bedrock categories described in section 3.2.

* where: very low = <2.0; low = 2.0–2.5; moderate = 2.5–3.0; high = 3.0–3.5; very high = >3.5; units are $W\ m^{-1}\ K^{-1}$

4 Geothermal data for Scotland

Heat flow is the standard measure of the amount of heat travelling through Earth‘s crust. As such, heat flow measurements have been used as the basis for all previous assessments of geothermal energy potential in Scotland. Unfortunately, the heat flow dataset for Scotland is relatively small, and no new values have been reported since the 1980s. Furthermore, the values are (as noted in section 2.1.4) subject to a range of factors that reduce the degree to which they can be assumed to provide an accurate indication of the size of the geothermal resource at depth. Making a significant step forward in our understanding of the deep geothermal energy potential in Scotland therefore requires either more heat flow data coupled with a better understanding of the factors that affect heat flow measurements, or an alternative means of assessing the size and distribution of the heat resource.

Temperatures measured directly in boreholes provide the best currently available alternative source of heat data. Available temperature data measured in onshore boreholes were collated and reported by Burley et al. (1984). The vast majority of the boreholes from which temperature data have been obtained were drilled for reasons other than geothermal energy assessment (usually oil/gas/coal exploration), and the data have not previously been evaluated in a geothermal energy context.

The heat flow and borehole temperature datasets for Scotland are reviewed in this section. Although this assessment of geothermal energy potential in Scotland is limited to onshore areas, temperature data obtained from offshore boreholes are included in the review because they increase the size of the dataset and extend the depth range of measured temperature data, thereby improving the confidence with which onshore data can be extrapolated to greater depths.

4.1 HEAT FLOW DATA

There are only thirty-five published heat flow values for Scotland (Table 3), all of which derive from onshore boreholes (Figure 4). Thirty-four of them are collated in the BGS Catalogue of Geothermal Data for the UK (Burley et al., 1984). The heat flow values range from 29 to 82 mW m^{-2}; the mean is 56 mW m^{-2} and the median is 57 mW m^{-2}. The geographical spread of the data, and contours derived from them, are shown in Figure 4 and Figure 5 together with the borehole names that appear in Table 3. The sparseness of the dataset is such that closed contours (indicating the location of apparent ‗hot spots‘) are formed in only two areas: in the central part of the Midland Valley, where a 60 mW m^{-2} contour encloses a cluster of values; and in the East Grampians region, where a 70 mW m^{-2} contour encloses a cluster of values derived from granite intrusions. The 50 mW m^{-2} contour in the East Grampians area has been extended tentatively to the west to intersect a cluster of values in Loch Ness. Most of the reported heat flow values derive from measurements made at depths of less than 400 metres below ground surface.

The following comments concern the degree to which these measurements can be considered to reflect accurately the size of the heat resource at depth.

- Nine values are from boreholes drilled into lake sediment on the floor of Loch Ness. The published values include significant corrections (e.g. for seasonal temperature variations in the water), so their reliability and the degree to which they can be compared meaningfully with values measured in solid rock are not clear; they should probably be treated with caution. Loch Ness overlies a major discontinuity in the crust, the Great Glen Fault, which may act to focus or disperse heat locally; the data therefore may not be a good indicator of regional background heat flow.

- Four values come from boreholes in radiogenic (HHP) granite in the East Grampians region, so these will be influenced by a local Heat Production component and will therefore not be a good indicator of regional background heat flow. These data are reviewed in more detail in section 8.2.
- Fifteen values are from boreholes sited in sedimentary rocks of Carboniferous and/or Devonian age. Of these, thirteen occur in geographical clusters: three are in Caithness (Achanarras, Houstrie of Dunn, Yarrows); three are close to Glenrothes in Fife (Glenrothes, Balfour, Boreland); and seven are in and around Glasgow (Clachie Bridge, South Balgray, Blythswood, Kipperoch, Barnhill, Hurlet, Maryhill). The two others are geographically isolated (Montrose, Marshall Meadows). The temperature of these sedimentary rocks may have been affected by large-scale convective transfer in groundwater, therefore it is unclear to what extent the heat flow measurements represent background heat flow values.
- The remaining seven measurements (from the Altnabreac A, Altnabreac B, Ballachulish, Meall Mhor, Tilleydesk and Castle Douglas boreholes, and an unnamed borehole on the east shore of Loch Fyne) were made in metamorphosed rocks that are not obviously affected by locally elevated Heat Production. Crystalline rocks lack intergranular porosity, and it has been generally assumed that they are ‗dry' at deep levels and heat transfer is essentially conductive. However, a growing body of evidence suggests crystalline rocks may also be affected to some degree by convective heat transfer in fracture-hosted groundwater. A value of 29 mW m^{-2} from the Tilleydesk (Ellon) borehole in Aberdeenshire is included in Burley et al. (1984) but was never formally reported by the Oxford University Heat Flow group that recorded it, presumably because it is a suspect value (as suggested by Lee et al., 1984); it is anomalously low, and cannot be considered a reliable indicator of background heat flow. With this value excluded from the heat flow dataset the mean value for all heat flow data for Scotland rises slightly to 57 mW m^{-2}.
- As noted previously (section 2.1.4), in all parts of Scotland the geothermal gradient in the near-surface zone is likely to be perturbed by climate warming since the last glaciation. For this reason, and for the variety of other reasons described above, the existing set of heat flow values for Scotland and the contours derived from them to produce the heat flow map (Figure 4 and Figure 5) almost certainly do not provide an accurate indication of the size and distribution of the heat resource at depth.

Region	Borehole name	Heat flow density (mW m^{-2})
Caithness	Altnabreac A	43
Caithness	Altnabreac B	53
Caithness	Achanarras	42
Caithness	Houstrie of Dunn	45
Caithness	Yarrows	52
Loch Ness	1	73
Loch Ness	2	64
Loch Ness	3	62
Loch Ness	4	57
Loch Ness	5	82
Loch Ness	6	67
Loch Ness	7	55
Loch Ness	8	43
Loch Ness	9	43
East Grampians	Tilleydesk (Ellon)	29
East Grampians	Cairngorm	70
East Grampians	Bennachie	76
East Grampians	Mt Battock	59
East Grampians	Ballater	71
Argyll	Ballachulish	53
Argyll	Meall Mhor	57
East Midland Valley	Montrose	46
East Midland Valley	Balfour	37
East Midland Valley	Boreland	40
East Midland Valley	Glenrothes	56
East Midland Valley	Marshall Meadows	51
East Midland Valley	Livingston	62
West Midland Valley	Clachie Bridge	55
West Midland Valley	South Balgray	72
West Midland Valley	Blythswood	59
West Midland Valley	Kipperoch	54
West Midland Valley	Barnhill	60
West Midland Valley	Hurlet	60
West Midland Valley	Maryhill	63
Dumfries & Galloway	Castle Douglas	61

Table 3 Heat flow data for Scotland. All data from Burley et al. (1984), except Glenrothes borehole from Brereton et al. (1988). ‗East Midland Valley' includes all boreholes in National Grid Reference 100 km squares NO and NT. ‗West Midland Valley' includes all boreholes in National Grid Reference 100 km square NS. Grid references for most boreholes are presented in Table 4. See Figure 4 for borehole locations.

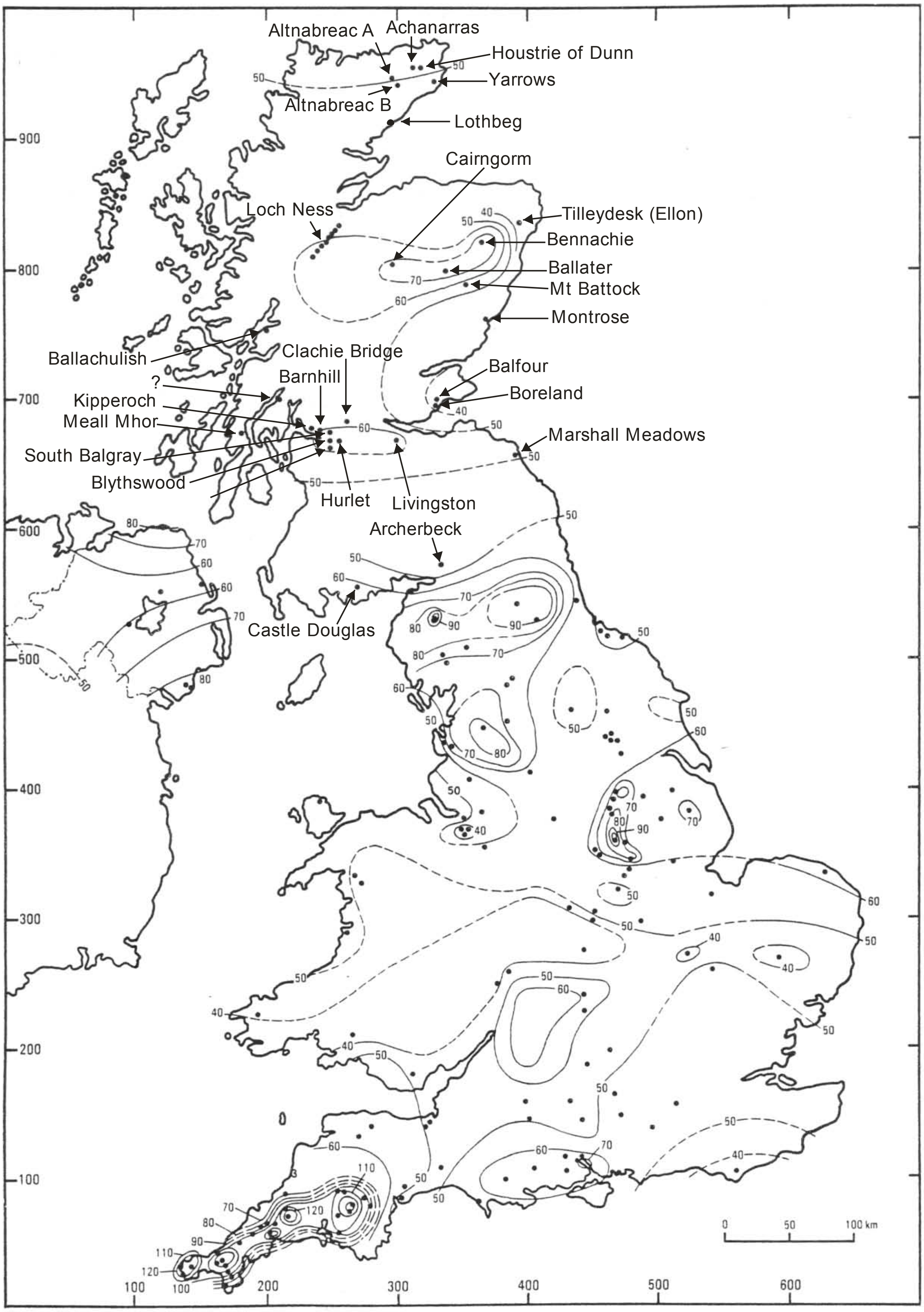


Figure 4 An early version of the heat flow map of the UK (from Lee et al., 1984; Figure 7.2). Black dots denote heat flow measurement localities. Names are boreholes referred to in Table 3. The locations of the Archerbeck and Lothbeg boreholes, which are not sites of heat flow measurement but are mentioned in section 7.4 and in Table 4, are also shown.

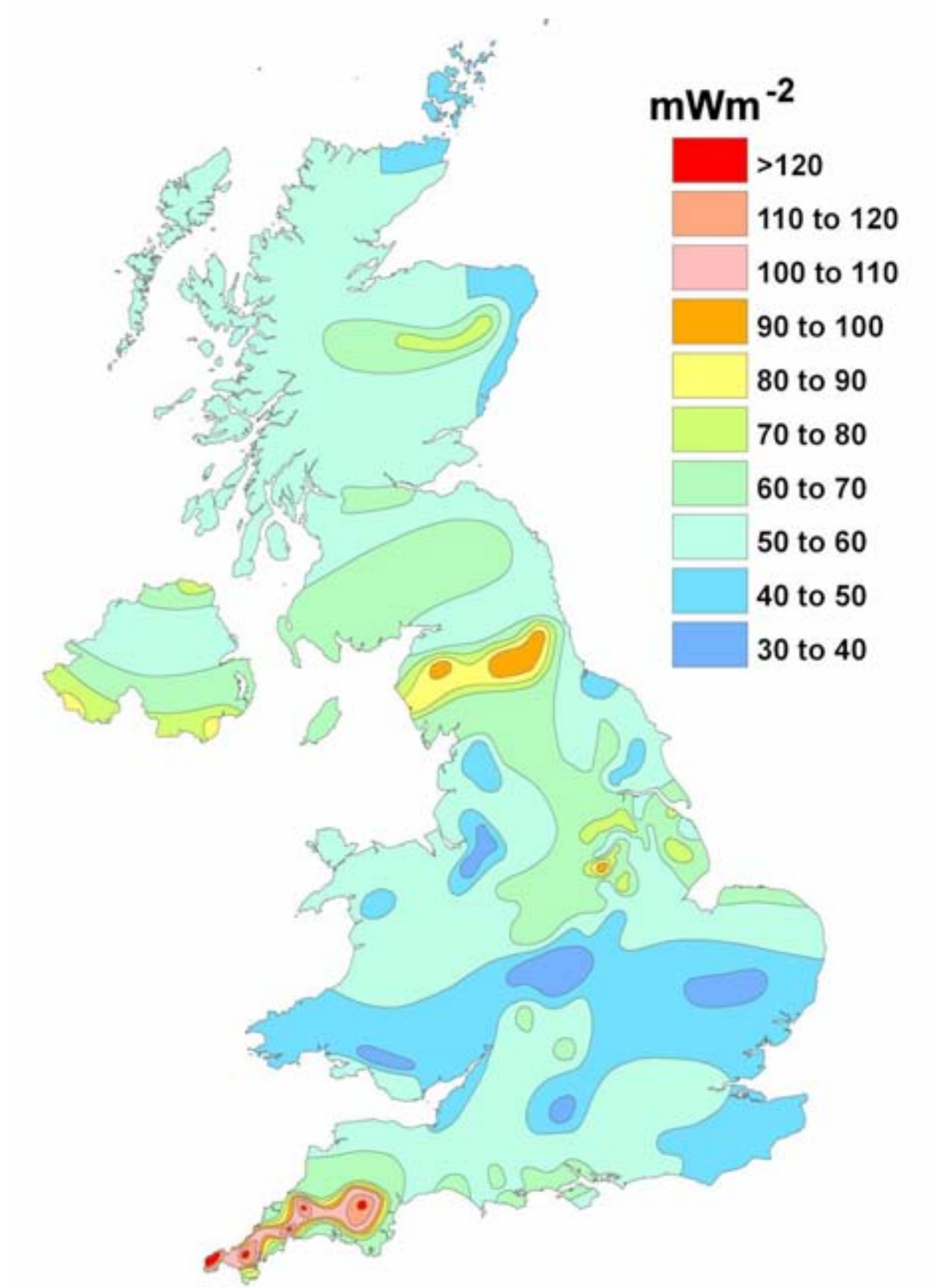


Figure 5 Colour-contoured heat flow map of the UK, based on the Geothermal Map of the UK (BGS, 1986; this version from Busby, 2010).

4.2 BOREHOLE TEMPERATURE DATA

4.2.1 Temperature data from onshore boreholes

The BGS Catalogue of Geothermal Data for the UK (Burley et al., 1984) includes a list of borehole temperature data for sixty-one 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 metres below ground surface, the onshore borehole temperature data extend to a depth of around 1,300 metres. Unfortunately, they are clustered mainly in Caithness, the East Grampians region, and particularly in the Midland Valley, and so do not significantly extend the spatial coverage of onshore geothermal data beyond that provided by the heat flow dataset.

Temperature data for onshore boreholes in Scotland are summarised in Table 4. An average temperature gradient has been calculated for each borehole using the surface temperature, the borehole temperature, and the depth at which the latter was measured. The range of average temperature gradient values for all sixty-one boreholes extends from 3.7 to 45.0ºC/km; the mean is 22.5ºC/km, and the median is 21.5ºC/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 (some combination of those described in sections 2.1.4 and 4.1). However, plotted together as temperature versus depth (T-z) the data display a trend defining a temperature gradient of 30.5ºC/km that persists throughout the entire depth range (Figure 6).

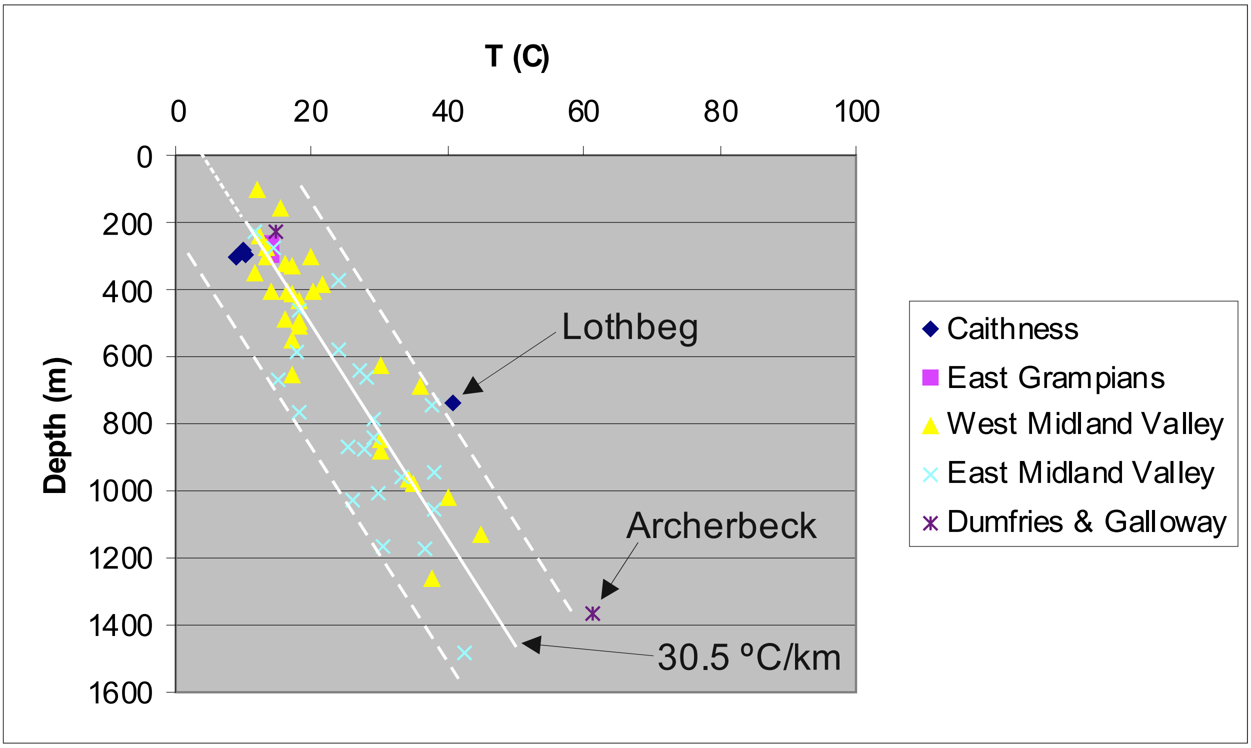


Figure 6 Bottom-hole temperature vs depth (T-z) data for onshore boreholes in Scotland. The trend of the data follows a temperature gradient of approximately 30.5ºC/km (solid white line). The dotted white line is an extrapolation of the solid line, intersecting the ‗surface' at 4ºC. Dashed white lines define the limits within which most of the data scatter around the centre line. See section 7.4 for a description of the Lothbeg and Archerbeck data.

Borehole name	Region	Grid reference	Source	Depth	Temp	T grad	Type
Altnabreac	Caithness	NC 9990 4528	BGS	299	10.3	7.4	LOG
Altnabreac	Caithness	NC 9939 4291	BGS	301	8.8	3.7	LOG
Altnabreac	Caithness	ND 0232 4167	BGS	282	10.1	7.1	LOG
Lothbeg No.1	Caithness	NC 946 095	PCO	736	40.6	42.9	BHT
Bennachie	East Grampians	NJ 6690 2110	BGS	294	14.0	20.1	BHT
Mt Battock	East Grampians	NO 543 905	BGS	263	14.0	22.1	BHT
Ballater	East Grampians	NO 4000 9850	BGS	296	14.0	19.6	BHT
Rashiehill	West Midland Valley	NS 8386 7301	BGS	964	34.4	26.2	LOG
Clachie Bridge	West Midland Valley	NS 6447 8368	BGS	300	13.2	16.0	LOG
Salsburgh	West Midland Valley	NS 8166 6486	GAS	883	30.0	24.1	BHT
Hallside	West Midland Valley	NS 6694 5975	BGS	350	11.8	6.0	LOG
Grangemouth	West Midland Valley	NS 9513 8387	NCB	1134	45.0	30.9	BHT
South Balgray	West Midland Valley	NS 50 75	BEN	160	15.3	45.0	EQM
Blythswood	West Midland Valley	NS 5003 6823	BEN	105	12.0	37.1	EQM
Douglas Colliery	West Midland Valley	NS 830 300	NCB	239	12.2	14.2	MWT
Solsgirth Colliery	West Midland Valley	NS 9777 9329	NCB	387	21.5	31.0	MWT
Bogside Colliery	West Midland Valley	NS 9564 8778	NCB	334	17.0	22.2	MWT
Highhouse Colliery	West Midland Valley	NS 5321 7202	NCB	436	18.0	19.5	MWT
Barony Colliery	West Midland Valley	NS 5105 1971	NCB	411	17.0	19.0	MWT
Killoch Colliery	West Midland Valley	NS 4883 2130	NCB	655	17.0	11.9	MWT
Polkemmet Colliery	West Midland Valley	NS 9190 6278	NCB	549	17.0	15.5	MWT
Eggerton	West Midland Valley	NS 8504 3171	NCB	410	14.0	13.2	BHT
Tillicoultry	West Midland Valley	NS 9276 9653	NCB	510	18.0	15.9	BHT
Tullibody	West Midland Valley	NS 8601 9594	NCB	325	16.0	18.8	BHT
Cartlove	West Midland Valley	NS 9403 9267	NCB	404	16.6	16.3	BHT
Gartenkeir	West Midland Valley	NS 9267 9486	NCB	488	16.0	15.0	BHT
Shannock Hill	West Midland Valley	NS 9338 9512	NCB	497	18.0	19.9	BHT
Pipersink	West Midland Valley	NS 9307 8911	NCB	408	20.2	25.5	BHT
Glenochill	West Midland Valley	NS 8769 9617	NCB	628	30.0	32.0	BHT
Queenslie	West Midland Valley	NS 6466 6598	NCB	691	36.0	38.4	BHT
Slatehole	West Midland Valley	NS 4906 2342	NCB	1024	40.0	29.8	BHT
Gallowknowe	West Midland Valley	NS 8388 3118	NCB	1261	37.5	22.8	BHT
Stoneyknowes	West Midland Valley	NS 8817 3570	BGS	277	13.5	18.1	BHT
Craighead	West Midland Valley	NS 8267 6212	TAW	977	35.0	27.2	BHT
Maryhill	West Midland Valley	NS 5718 6856	IC6	303	20.0	34.0	EQM
Comrie	West Midland Valley	NS 9787 9501	NCB	850	30.0	24.1	VST

Borehole name	Region	Grid reference	Source	Depth	Temp	T grad	Type
Glenrothes	East Midland Valley	NO 2561 0314	BGS	279	14.4	28.1	EQM
Balfour	East Midland Valley	NO 323 003	BEN	1205	33.4	19.8	EQM
Windygates	East Midland Valley	NO 3510 0034	NCB	1298	30.0	16.1	BHT
Spilmersford	East Midland Valley	NT 4570 6902	BGS	877	27.8	20.9	BHT
Midlothian	East Midland Valley	NT 363 647	ESO	747	37.8	39.1	LOG
Birnieknowes	East Midland Valley	NT 7580 7317	BGS	372	23.9	39.2	LOG
Marshall Meadow	East Midland Valley	NT 9797 5686	IC5	227	11.5	10.6	EQM
Cousland No.5	East Midland Valley	NT 3774 6773	BP	585	17.8	15.0	BHT
Cousland No.6	East Midland Valley	NT 3835 6801	BP	582	23.9	25.6	BHT
Pumpherston	East Midland Valley	NT 0733 6979	BP	1175	36.7	23.3	BHT
Lochead	East Midland Valley	NT 3219 9659	NCB	1167	30.4	17.7	BHT
Boreland	East Midland Valley	NT 3040 9420	AND	1007	29.8	20.1	EQM
Mackies Mill	East Midland Valley	NT 3050 9795	NCB	960	33.3	24.6	BHT
Thornton Bridge	East Midland Valley	NT 2889 9722	NCB	665	28.0	27.5	BHT
Thornton Farm	East Midland Valley	NT 2969 9761	NCB	1055	38.0	26.8	BHT
Eastfield	East Midland Valley	NT 3264 7297	NCB	1028	26.0	15.6	BHT
Bilston Glen Colliery	East Midland Valley	NT 2996 6320	NCB	670	15.0	8.7	MWT
Lady Victoria Colliery	East Midland Valley	NT 3294 6666	NCB	768	18.0	10.8	MWT
Auchendinny	East Midland Valley	NT 2496 6125	NCB	459	18.0	19.6	BHT
Wellsgreen	East Midland Valley	NT 3342 9833	NCB	1485	42.3	22.0	LOG
Livingston	East Midland Valley	NT 018 691	OX3	640	27.0	28.1	EQM
Stewart	East Midland Valley	NT 3633 6476	LAS	942	37.9	34.9	BHT
Frances	East Midland Valley	NT 3214 9050	NCB	841	29.0	23.8	VST
Monktonhall	East Midland Valley	NT 3242 7053	NCB	866	25.5	18.2	VST
Seafield	East Midland Valley	NT 3150 8923	NCB	789	29.0	25.3	VST
Castle Douglas	Dumfries & Galloway	NX 717 550	OX5	231	14.7	23.8	EQM
Archerbeck	Dumfries & Galloway	NY 4157 7815	BGS	1365	61.2	37.9	LOG

Table 4 Temperature-depth data for onshore boreholes in Scotland.

All data are from Burley et al. (1984), except Glenrothes which is from Brereton et al. (1988). ‗East Midland Valley‘ includes all boreholes in National Grid Reference 100 km squares NO and NT. ‗West Midland Valley‘ includes all boreholes in National Grid Reference 100 km square NS. BGS = British Geological Survey, PCO = Premier Consolidated Oilfields, GAS = British Gas Corporation (as was), NCB = National Coal Board (as was), BEN = Benfield (1939), TAW = Taylor Woodrow Energy (as was), IC6 = Wheildon et al. (1984), ESO = Esso, IC5 = pers. comm. (to Burley et al., 1984) from J Wheildon, BP = British Petroleum (as was), AND = Anderson (1940), OX3 = Bloomer et al. (1979), LAS = Lasmo, OX5 = Oxburgh (1982). Depths are in metres measured from the ground surface; temperatures are in ºC; T grad = temperature gradient, in ^{o}C/km. Type: LOG = T measured during geophysical logging; BHT = bottom-hole temperature; EQM = equilibrium temperature; MWT = mine water temperature; VST = virgin strata (= equilibrium) temperature. Full descriptions of these terms and the reliability of the associated measurements are given in Burley et al. (1984). Surface temperatures for each borehole, which are required to calculate T grad, are given in Burley et al. (1984).

When extrapolated, the best-fit line through all the data intersects the ‗surface' (0 metres on the depth axis of Figure 6) at approximately 4.0ºC; this is significantly below the current annual average surface temperature in Scotland (taken to be 9.0ºC, which is the average of all the surface temperature data listed in Burley et al. (1984) for the boreholes included in Table 4). 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. The geothermal gradient measured in the near-subsurface will therefore be lower than the temperature gradient defined by all the borehole temperature data (30.5ºC/km). Hence, measurements of the geothermal gradient made in individual shallow boreholes are likely to underestimate the actual geothermal gradient at depth. It follows that heat flow values calculated using these geothermal gradient data will underestimate the size of the heat resource at depth.

4.2.2 Temperature data from offshore boreholes

Most of the boreholes in offshore parts of Scotland have been drilled by hydrocarbon exploration companies; such boreholes are typically referred to as wells. Bottom-hole temperature (BHT) data from seventy-two wells drilled into thirteen ‗sectors' on the North West Margin of the UK continental shelf are compiled in Gatliff et al. (1996). The location of the wells and sectors is shown in Figure 7. Details of the sectors and well numbers, corrected[2] bottom-hole temperatures

[2] The friction caused by drilling, and the effect of introducing lubricating fluid, can temporarily change the temperature of the rock lining a borehole. Immediately after drilling, the rock temperature at shallow depths is typically hotter than it is naturally, while at deeper levels it is typically cooler than it is naturally. It can take many months or even years for rock temperature to return to its natural equilibrium condition after drilling. For this reason, it is generally best to measure borehole temperature some time after drilling has ceased. In many cases this is not possible, so a correction factor is applied to the measured temperatures to account for the temporary change.

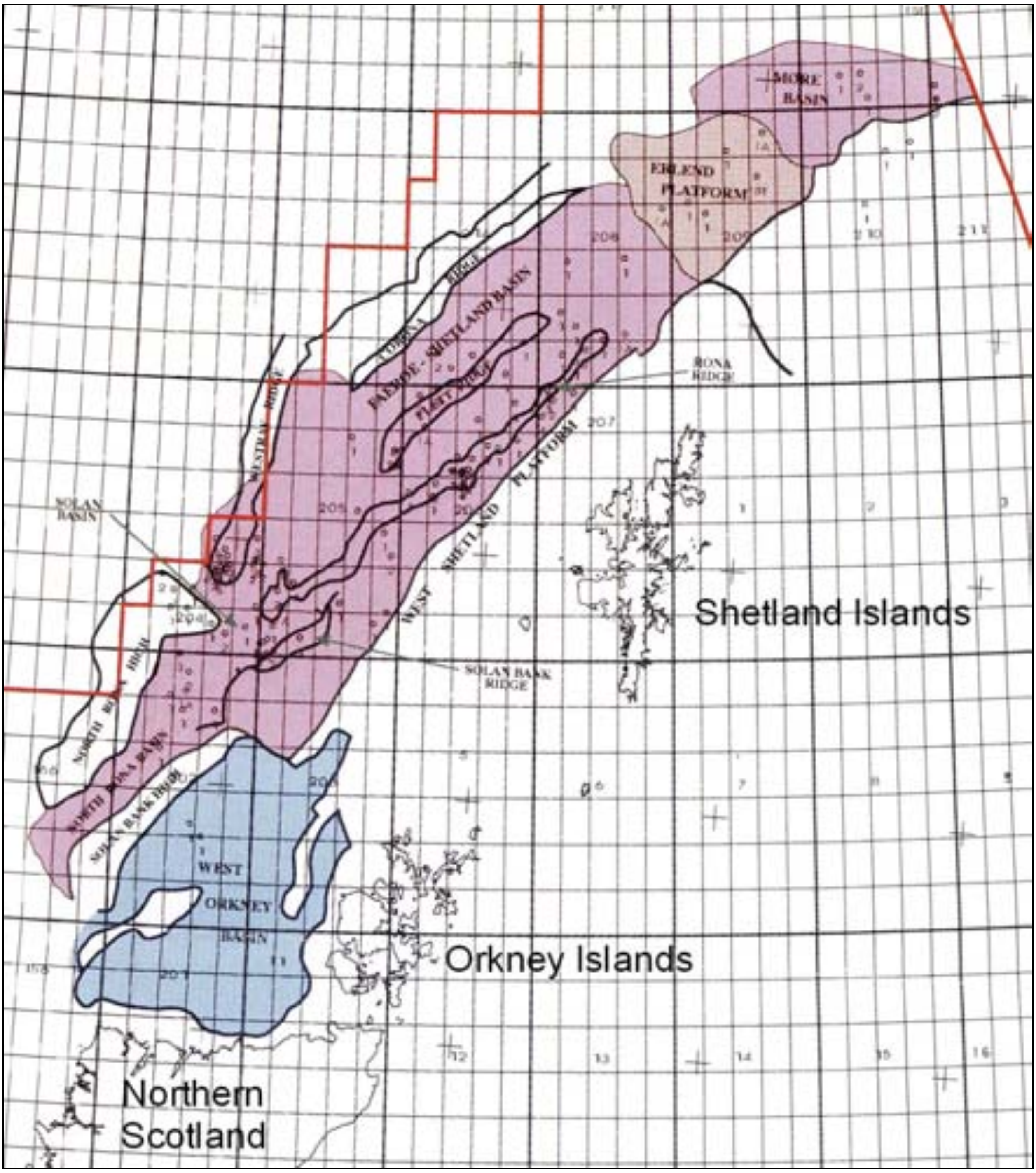
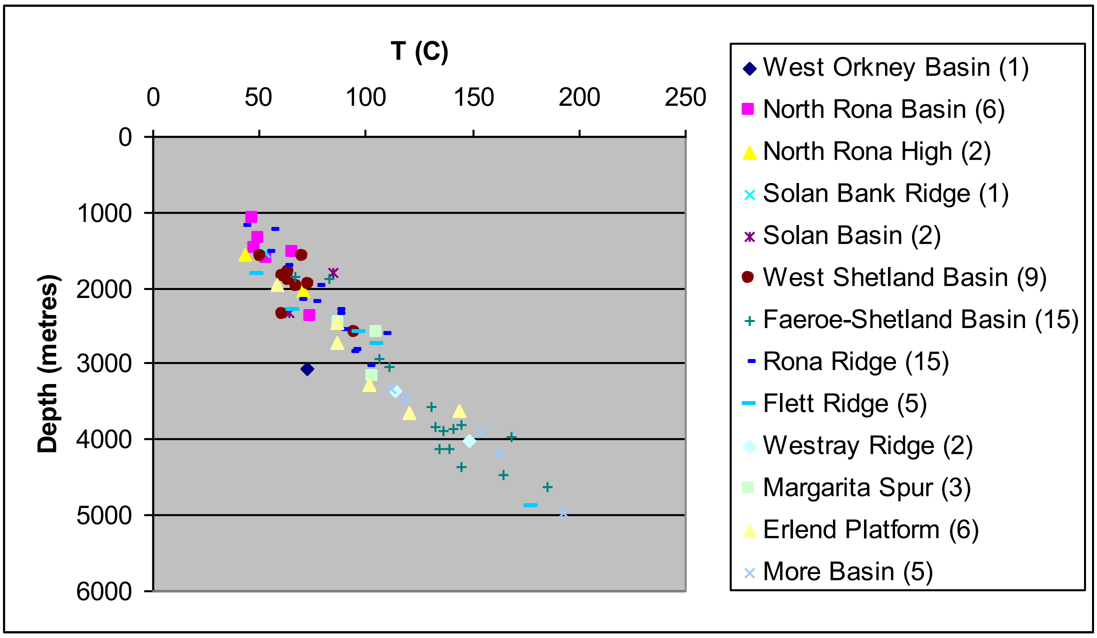


Figure 7 Well and sector locations in the North West Margin. From Gatliff et al. (1996).

a)



(b)

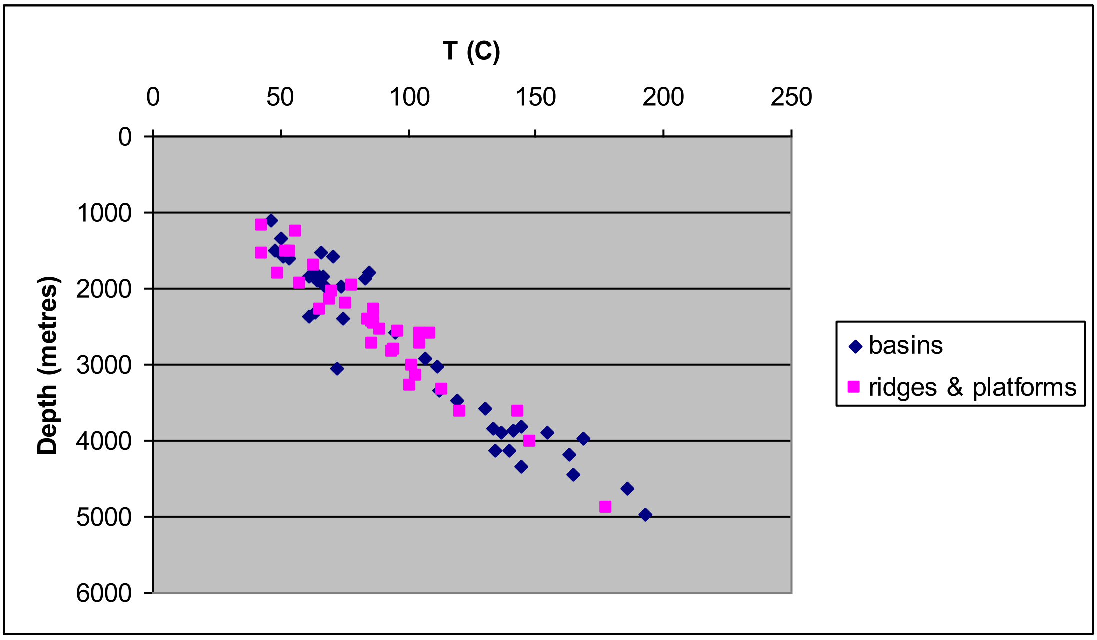


Figure 8 Bottom-hole temperature versus depth (T-z) data for offshore wells in the North West Margin. (a) Data plotted according to sector. (b) Data plotted according to structural setting (structurally ‗low' geological basins and structurally ‗high' ridges and platforms).

Sector	Well no.	T (ºC)	Depth (m)	Seabed T (ºC)	T grad (ºC/km)
West Orkney Basin	202/19-1	72.1	3065	9	20.6
North Rona Basin	202/2-1	46.6	1094	9	34.4
	202/3-1A	53.2	1612	9	27.4
	202/3-2	49.9	1347	9	30.4
	202/3A-3	74.3	2384	9	27.4
	202/8-1	66.1	1538	9	37.1
	202/9-1	47.9	1493	9	26.1
	204/28-1	43.2	1565	8	22.5
North Rona High	204/29-1	70.7	2046	9	30.2
Solan Bank Ridge	205/27A-1	52.8	1538	9	28.5
Solan Basin	204/30-1	84.9	1801	9	42.1
	205/26A-2	63.7	2322	9	23.6
West Shetland Basin	205/20-1	63.7	1801	9	30.4
	205/23-1	94.8	2585	9	33.2
	205/25-1	61.3	2363	9	22.1
	205/30-1	67.2	1981	9	29.4
	206/13-1	51.2	1576	9	26.8
	207/1-2	70.4	1584	9	38.8
	207/2-1	64	1892	9	29.1
	208/23-1	61.5	1854	9	28.3
	208/24-1A	73.6	1962	9	32.9
Faeroe-Shetland Basin	205/16-1	168.5	3964	9	40.2
	206/1-2	136.6	3884	3	34.4
	206/2-1A	141.2	3872	3	35.7
	206/3-1	185.6	4626	9	38.2
	206/5-1	132.9	3838	9	32.3
	206/11-1	144.5	4354	9	31.1
	208/17-1	139.5	4123	3	33.1
	208/19-1	106.2	2928	9	33.2
	208/21-1	111.2	3038	8	34.0
	208/22-1	83	1878	9	39.4
	208/26-1A	130.3	3581	9	33.9
	214/27-1	144.5	3805	3	37.2
	214/27-2	66.7	1845	3	34.5
	214/28-1	164.3	4460	3	36.2
	214/29-1	134	4119	8	30.6
Rona Ridge	205/21-1A	42.9	1184	9	28.6
	205/22-1A	101.9	3027	9	30.7
	206/8-1A	69.5	2163	9	28.0
	206/8-2	63.1	1720	9	31.5
	206/8-3	84.8	2416	9	31.4
	206/8-4	94.4	2848	9	30.0
	206/8-5	78.4	1970	9	35.2
	206/8-6	89	2560	9	31.3
	206/8-7	76	2200	9	30.5
	206/9-1	109.2	2612	9	38.4
	206/9-2	87.3	2297	9	34.1
	206/10A-1	95	2826	9	30.4
	206/12-1	54.3	1537	9	29.5
	206/12-2	87.3	2364	9	33.1
	207/1-1	56.6	1251	9	38.0
Flett Ridge	205/10-1A	49.1	1815	8	22.6
	205/10-2	177.9	4900	8	34.7
	205/10-3	65.5	2294	8	25.1
	206/1-1A	96.7	2578	8	34.4
	214/30-1	105	2748	8	35.3
Westray Ridge	204/19-1	148.1	4023	3	36.1
	204/23-1	113.3	3349	8	31.4
Margarita Spur	210/4-1	87.1	2462	9	31.7
	210/5-1	105.2	2600	9	37.0
	210/13-1	103.2	3159	10	29.5
Erlend Platform	208/15-1A	86.2	2733	9	28.2
	209/3-1A	58.1	1953	9	25.1
	209/4-1A	120.5	3637	9	30.7
	209/6-1	143.6	3629	9	37.1
	209/9-1	86.2	2447	9	31.5
	209/12-1	101.3	3279	9	28.1
Møre Basin	219/20-1	162.8	4187	5	37.7
	219/27-1	112.1	3335	9	30.9
	219/28-2	118.8	3466	8	32.0
	220/26-1	193.1	4961	9	37.1
	220/26-2	154.3	3902	9	37.2

Table 5 Bottom-hole temperature and depth data for offshore wells in the North West Margin region. Data from Gatliff et al. (1996). Depths are measured from the sea bed.

(CBHT), depths below seabed and temperature at seabed are presented in Table 5, along with calculated values for the average temperature gradient in each well. The data span a depth range from 1,094 to 4,961 metres below the sea bed, by far the deepest and greatest depth range for published geothermal data in any part of Scotland. The range of average temperature gradient values for individual wells is 20.6 to 42.1ºC/km; the mean is 31.9ºC/km, and the median is 31.5ºC/km.

As with the equivalent data from onshore boreholes, the wide range of average temperature gradient values suggests that the gradient in any one well is affected by a range of local factors. However, plotted together in temperature-depth (T-z) space the data define a clear trend that spans the entire depth range (Figure 8 a,b), from which the following observations can be made:

- the trend is defined equally clearly by wells representing single sectors and wells representing all sectors;
- the trend is the same for wells drilled into geological ‘highs’ (ridges and platforms) and geological ‘lows’ (basins);
- the trend is not straight; its shape is probably best characterised as a gentle curve denoting increasing temperature gradient with depth;
- the temperature gradient for the top part of the trend (defined by data extending down to c. 3.5 km) is approximately 36ºC/km, while for the bottom part (defined by data below c. 3.5.km) it is approximately 47ºC/km;
- the trend suggests a temperature of ~190ºC would be encountered at a depth of 5 km across the North West Margin.

Gatliff et al. (1996) provided geological details for fifteen of the wells. This subset includes at least one representative from all thirteen sectors of the North West Margin, with the exception of the Margarita Spur sector. All of the wells intersect a thick sequence of sedimentary rocks, representing every period of geological time from the Devonian (c. 400 million years ago) to the Quaternary (present day) period. Most of the wells terminate in sedimentary (cover) rocks, but three of the fifteen wells terminate in crystalline basement rocks.

4.2.3 Combined temperature data for onshore boreholes and offshore wells

Plotted together, the temperature-depth (T-z) data for onshore boreholes and offshore wells define a single, linear trend that extends from the near-surface down to 5 km (Figure 9). The following observations can be made.

- None of the 133 data points lie significantly off the trend, raising the possibility that a consistent regional temperature gradient exists beneath much (possibly all) of Scotland.
- The relatively modest amount of scatter displayed by the data is noteworthy, considering the variety of geological settings, the geographical extent of the data (c. 900 km from north to south), the lack of a common datum for depth measurements (onshore depths are calculated with respect to ground surface and offshore depths with respect to the sea bed), and the range of factors that can influence heat supply and transfer.
- The temperature range defined by the data at any one depth is never greater than 46ºC, and this range is broadly consistent at all depths (Figure 9).
- If the centre-line of the trend is taken to represent a regional temperature gradient, the ~46ºC temperature range at any one depth represents the maximum net effect of inaccuracies in temperature measurements and variations in surface elevation, borehole equilibration time, thermal conductivity, climate change

signal, convective heat transfer, background heat supply and locally generated heat.

- The consistency of the trend and limited scatter of the data suggests that the temperature at any given depth down to 5 km can be predicted with a precision of approximately ±23 °C. In other words, the pattern of background heat flow beneath Scotland may be relatively simple and largely predictable.
- The temperature gradient defined by all the data is not constant (i.e. a straight line), but increases with depth. The gradient is probably best described as a curve, but on Figure 9 it is divided into three best-fit straight-line segments for which separate geothermal gradients can be calculated. In the top 1.5 km the gradient is approximately 30.5ºC/km, between 1.5 and 3.5 km it is 35.8ºC/km and between 3.5 and 5 km it is 46.7ºC/km.
- Compaction of sedimentary rocks should increase their thermal conductivity, hence the geothermal gradient in sedimentary rocks should, in general, decrease with increasing depth if the heat flow profile is consistent.
- The apparent gradual increase in geothermal gradient with depth is not easily explained. Climate warming since the last glaciation (see section 2.1.4) may account (at least in part) for a lower geothermal gradient in the shallowest part of the curve, while the proximity of some offshore areas to the continental margin (where the crust may be thinner and heat flow therefore may be higher) may account (at least in part) for a higher geothermal gradient in the deepest part of the curve.
- The trend is defined by data from boreholes and wells that penetrate a range of rock types and structural regimes both onshore and offshore, and is essentially continuous throughout the zone in which the deepest onshore data and shallowest offshore data overlap; this suggests the regional temperature gradient may be broadly the same in both onshore and offshore settings.

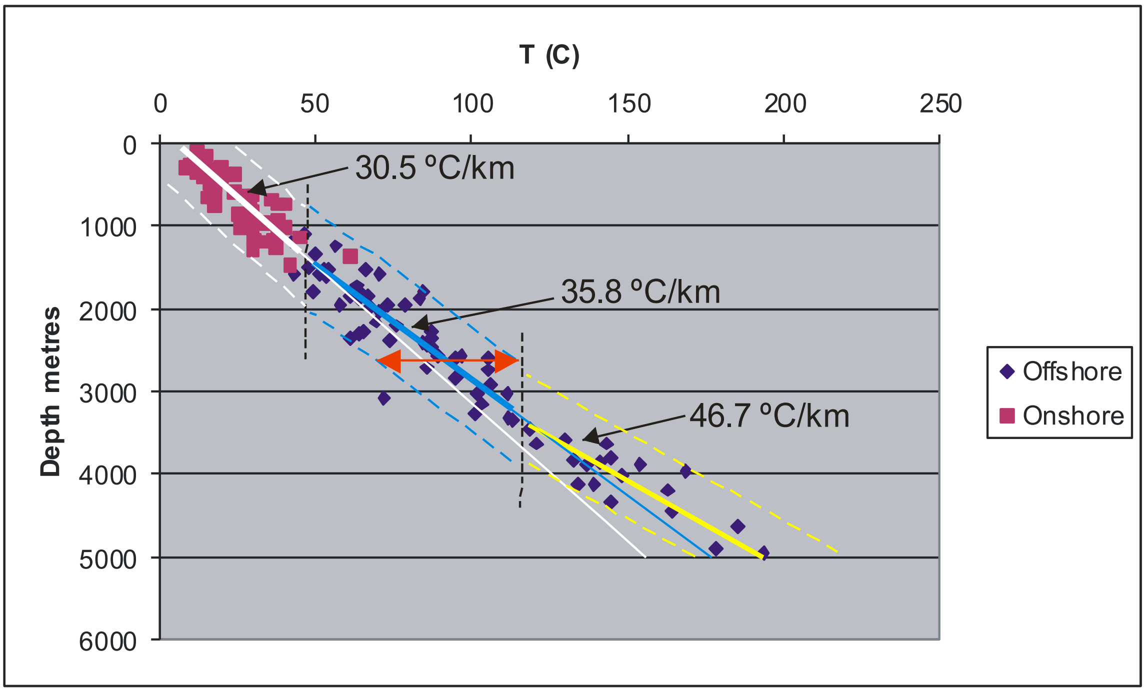


Figure 9 Combined onshore and offshore bottom-hole temperature vs depth data. Solid white, blue and yellow lines represent the centre line of the averaged geothermal gradient in three depth ranges, 0–1,500, 1,500–3,500 and 3,500–5,000 metres respectively. Dashed white, blue and yellow lines mark the approximate limits of the data scatter to either side of the centre line. The red

double-headed arrow marks the depth at which the temperature data are most widely scattered; the arrow spans a temperature range of ~46°C.

Much of onshore Scotland is underlain by crystalline rocks. Unfortunately, there are very few temperature data from crystalline rocks in onshore parts of Scotland, and none from deeper than 300 metres below ground surface. However, sixteen of the wells forming the North West Margin dataset terminated in the crystalline (basement) rocks that underlie the sedimentary (cover) rocks. The bottom-hole temperatures in these wells therefore represent temperature data for crystalline rocks. The T-z trends for wells that terminate in crystalline basement rocks and wells that terminate in non-crystalline (sedimentary) cover rocks are essentially identical (Figure 10), suggesting the regional temperature gradient extends unperturbed across the basement-cover interface.

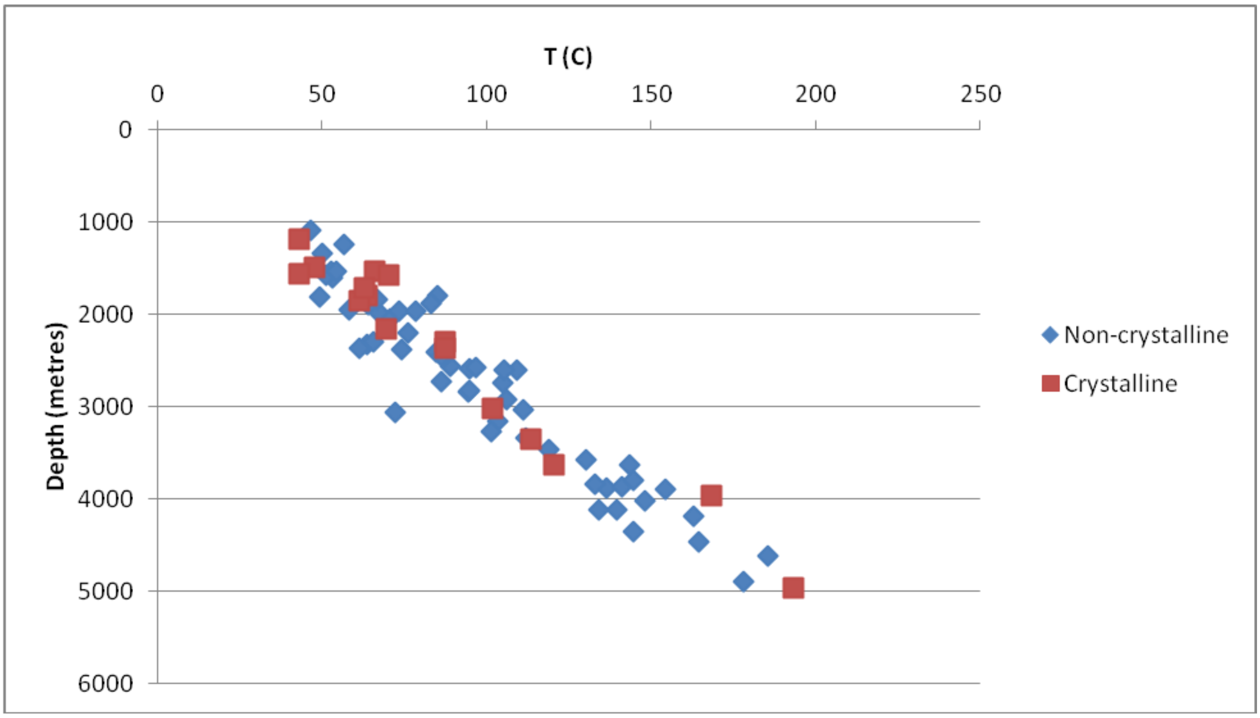


Figure 10 Bottom-hole temperature versus depth (T-z) data for offshore wells in the North West Margin, distinguishing those that terminated in non-crystalline (sedimentary cover) and crystalline (igneous or metamorphic basement) rocks.

Even if onshore settings do not follow the higher temperature gradient of offshore settings below 1.5 km, the gradient of 30.5ºC/km defined by the data from onshore boreholes suggests temperatures could be around 150ºC 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. The extrapolation must carry a lower level of confidence for other onshore areas for which there are temperature data (Caithness, East Grampians and Dumfries & Galloway), because there are fewer data for these areas and they span a relatively shallow depth-range. None of the data for these areas lies significantly off the trend so there is currently no indication that the regional temperature gradient outside the Midland Valley is significantly different from that within it. However, sedimentary basins (such as the Midland Valley) commonly form as a result of the crust being stretched, which means the crust beneath sedimentary basins can be relatively thin and therefore heat flow can be higher than in adjacent areas underlain by thicker crust.

5 Key conclusions and recommendations arising from Part 1

5.1 CONCLUSIONS

1. Scotland occupies an essentially stable geological setting and doesn‘t obviously have a substantial accessible resource of deep geothermal energy. However, in common with all parts of the globe, the crust beneath Scotland contains a vast store of heat. The challenge is to understand how that heat is distributed, laterally and vertically, and to identify where resources occur that are sufficiently large and sufficiently accessible to form commercially viable prospects.

2. Heat flow measurements are the primary means of assessing the size of the heat resource. Thirty-five published heat flow values for Scotland are discouragingly low. The values range from 29 to 82 mW m^{-2}, with a mean of 56 mW m^{-2}. The mean value is somewhat lower than the mean across all continents (65 mW m^{-2}), and significantly lower than values usually associated with exploitable resources of deep geothermal energy.

3. A growing body of research has shown that heat flow values can be significantly affected by local perturbations in the shallow geothermal regime. In particular, the effect of recent, post-glaciation warming on the shallowest part of the geothermal gradient means heat flow values in Scotland (and other areas affected by glaciation) are likely significantly to underestimate the heat resource at depth. Published data suggest that recent changes in the climate may have suppressed near-surface heat flow by as much as 60% in some parts of northern Europe and North America. Preliminary, unpublished work by BGS indicates that heat flow values in the East Grampians region of Scotland may be suppressed by up to 29%. These findings suggest that heat flow below the climate-affected zone in Scotland (which may extend to a depth of around 2 km) is significantly greater than previously assumed.

4. Bottom-hole temperature (BHT) measurements in boreholes provide an alternative set of measured thermal data which previously have not been assessed in the context of geothermal energy. BHT versus depth (T-z) data for sixty-one onshore boreholes in mainland Scotland and seventy-two offshore boreholes (wells) in the North West Margin area (north of the Scottish mainland and west of the Orkney and Shetland islands) define a single linear trend that extends to a depth of at least 5 km. None of the 133 BHT data lie significantly off the trend, suggesting that rock temperature in large parts of the crust beneath Scotland increases with depth in a broadly consistent, and therefore largely predictable, way. The trend is not obviously affected by the fact that the dataset includes temperature measurements made in onshore and offshore settings, basin and ridge settings, and in crystalline and non-crystalline rocks. The geographical spread of the data is patchy; however, their considerable geographical extent (over 900 km from north to south) and the continuity of the trend throughout the full 5 km depth range raise the possibility that the trend represents a general regional geothermal gradient for Scotland.

5. The trend defined by the T-z data is slightly curved: in the top 1.5 km (defined mainly by data from onshore boreholes) the gradient is approximately 30ºC/km; between 1.5 and 3.5 km it is 36ºC/km and between 3.5 and 5 km it is 47ºC/km. Climate warming since the last glaciation may account (at least in part) for a lower geothermal gradient in the shallowest part of the curve, while the proximity of some offshore areas to the continental margin (where the crust may be thinner and heat flow therefore may be higher) may account (at least in part) for a higher geothermal gradient in the deepest part of the curve.

6. In the North West Margin area the temperature at 5 km is around 190ºC. If the trend defined by the T-z data represents a regional temperature gradient, similar temperature values should be encountered at the same depth in onshore settings. Even if onshore settings do not follow the higher temperature gradient of offshore settings below 1.5 km, the gradient of 30ºC/km defined by the data from onshore boreholes suggests temperatures of around 150ºC would be encountered at 5 km in onshore settings. These results suggest the temperature gradient in the crust beneath Scotland is significantly higher and more consistent regionally than has been thought hitherto.

7. In onshore parts of Scotland, deep geothermal energy prospects can be classified in terms of three broad settings: abandoned mine workings, Hot Sedimentary Aquifers (HSA), and Hot Dry Rocks (HDR). The first two of these are hydrothermal systems (i.e. the energy resides in heated water), and the last is a petrothermal system (i.e. the energy resides in hot rock).

    7.1. Mining creates additional permeability within strata that otherwise typically have relatively lower permeability; the heat within mine water can be exploited using Ground Source Heat Pump (GSHP) technology.

    7.2. In the HSA concept, the heat energy is contained in naturally permeable, water-bearing rocks (aquifers); warm or hot water extracted from the aquifer can be used for heating.

    7.3. In the HDR concept, the heat energy is contained in rocks that have very low permeability and are therefore essentially dry; an Enhanced (or Engineered) Geothermal System (EGS) must be developed to introduce cold water into the hot rocks, recover heated vapour and water from them, and generate electricity.

5.2 RECOMMENDATIONS

The regional geothermal regime beneath Scotland is still relatively poorly understood. A better understanding of the regional distribution of heat, both laterally and vertically, in shallow parts of the crust is needed before decisions are made regarding the location and design of more detailed, site-specific studies. The following steps should be considered.

R1 Model the effect on the geothermal gradient of post-glacial warming

The extent to which the geothermal gradient at shallow depths is affected by geologically recent climate change (specifically warming since the last glaciation) needs to be determined, so that: (i) accurate corrections can be applied to past and future measurements of heat flow in shallow boreholes, and (ii) meaningful extrapolations can be made of heat flow values to greater depths. Current knowledge of the spatial and temporal distribution of glacial, periglacial and interglacial conditions in Scotland, and the ground surface temperatures associated with each, could be used to model mean surface temperatures during and at the end of the last glacial period, from which can be deduced the magnitude of post-glacial warming and its likely effect on the shape of the geothermal gradient curve in the shallow subsurface. Some academic research addressing this issue in Scotland may already be underway.

R2 Improve the heat flow dataset for Scotland

Contours on the present heat flow map of Scotland are constrained by only a handful of widely scattered (and locally closely clustered) data, leading to a generalised representation. The effect of so few data is to draw attention to a few areas of apparent above average heat flow, and simultaneously to deflect attention from large parts of the country for which there are no heat flow data. Most of the existing heat flow data for Scotland come from relatively shallow boreholes, and none come from anywhere close to the depth required (>2 km) to exceed the potential limit of a transient post-glacial warming signal. More heat flow data should be gathered to improve the dataset for Scotland in terms of both depth (the deeper the better) and geographical coverage. Deepening existing onshore boreholes might provide a relatively cheap means of obtaining heat flow data from relatively deep levels in some parts of the country. The possibility should also be explored of obtaining heat flow data from offshore deep hydrocarbon exploration wells, particularly those that penetrate basement rocks.

R3 Extend the bottom-hole temperature versus depth (T-z) dataset to include all available data for Scotland

This would improve our understanding of the degree to which the geothermal regime beneath Scotland is characterised by a single regional geothermal gradient (as is suggested by the data presented in section 4.2). Most of the T-z data presented in section 4.2 come from offshore wells, but the dataset is limited to published data from the North West Margin area. T-z data for the numerous wells that have been drilled in other parts of offshore Scotland (principally the North Sea but also around the Northern Isles and Hebrides) should be obtained to augment the dataset; these data are probably largely unpublished but will be held by the Department of Energy & Climate Change (DECC). The assessment presented in section 4.2 includes all of the available T-z data for onshore boreholes in Scotland, but the possibility should be considered of expanding the dataset by measuring bottom-hole temperatures in existing accessible onshore boreholes for which no temperature data currently exist.

Part 2

Deep geothermal energy potential in Scotland

In Part 2 of this report, the deep geothermal energy potential in onshore parts of Scotland is considered in terms of three main settings: abandoned mine workings; hot sedimentary aquifers; and hot dry/wet rocks.

Although at this stage it must be treated with caution (at least in some parts of the country), the regional temperature gradient derived from borehole temperature data (described in section 4.2) nevertheless currently provides probably the most reliable insight into the size and distribution of the heat resource at depth beneath Scotland. It is therefore used in Part 2 to help assess the geothermal energy potential in different parts of the country. The small degree of scatter shown by data that define the gradient at all depths down to 5,000 metres means that isotherms (surfaces representing a constant temperature) in a 3D model would be represented simply as horizontal planes that ignore changes in bedrock geology. A 3D model illustrating this simple situation is not particularly helpful, therefore, so the distribution of areas that may have deep geothermal energy potential is instead illustrated in the following sections of this report using maps.

6 Abandoned mine workings

6.1 INTRODUCTION

Virtually all geological formations in the UK have the capacity to store sufficient heat to support the use of small-scale (closed loop) GSHP systems for space heating. For most of the UK, groundwater temperatures at typical abstraction depths of up to 100 m are around 10 to 12°C and essentially stable throughout the year (Ó Dochartaigh, 2009).

However, most large scale GSHP systems, serving more than a single home, are open-loop systems. Such systems generally require high abstraction rates, often in excess of 20 litres/second (l/s), from one or several boreholes (Ó Dochartaigh, 2009). This is in the upper range of potential yields from Scottish aquifers. For example, the Carboniferous sedimentary aquifers in the Midland Valley, in their natural, undisturbed state, are thought generally to form moderately productive aquifers, capable of providing borehole yields that are normally in the range 5 to 15 l/s (MacDonald et al., 2004; Robins, 1990; Ball, 1999).

Most of the abandoned mine workings in Scotland are former coal mines; however, underground mining was also used to extract ironstone, limestone, oil-shale, lead, gold, silver and other minerals (Figure 11).

Underground mining involves the removal of rock from the ground, producing voids in the rock. In longwall and shortwall mining, much of this artificially produced void space often becomes closed again by controlled collapse of failure of roof support subsidence, but mining activity leaves a net gain in the amount of pore space in the subsurface.

The permeability of the subsurface is artificially enhanced in previously mined areas due to:

- increased void space in zones where seams were mined out;
- potential increase in fracturing in competent horizons above mined seams due to stressing during subsidence;
- remnant shafts and roadways, which provide large diameter artificial flow pathways.

Transmissivity estimates for mined rock are rare, and none are known for the Carboniferous rocks Scotland. However, there are many records of boreholes intercepting mine workings in the Glasgow area which were pumped at yields of more than 30 l/s, and at least one record of a dewatering borehole pumped at more than 150 l/s (Ó Dochartaigh, 2009).

Abandoned, sometimes collapsed, and flooded mine workings have very large surface areas (and subsurface [flooded] volumes); these rock-water interfaces provide significant potential for heat exchange (Banks et al., 2003; PB Power, 2004). This, and the associated potential high abstraction rates related to artificially enhanced permeability, makes them of interest for large, open-loop ground source heat pump systems (Banks et al., 2003).

Groundwater in mined areas is usually of poor quality (section 6.4.3) and is otherwise an unused resource. In some cases, the water is being pumped and treated to prevent or reduce discharge of poor quality water to water courses.

The potential for abstraction of groundwater from mined areas, and utilising the heat energy it contains, is therefore greatly enhanced by mining activities. Characterising and quantifying this enhanced porosity and permeability, as well as other features of the groundwater system, is therefore needed in the development of this potentially large source of low-carbon energy using GSHP systems.

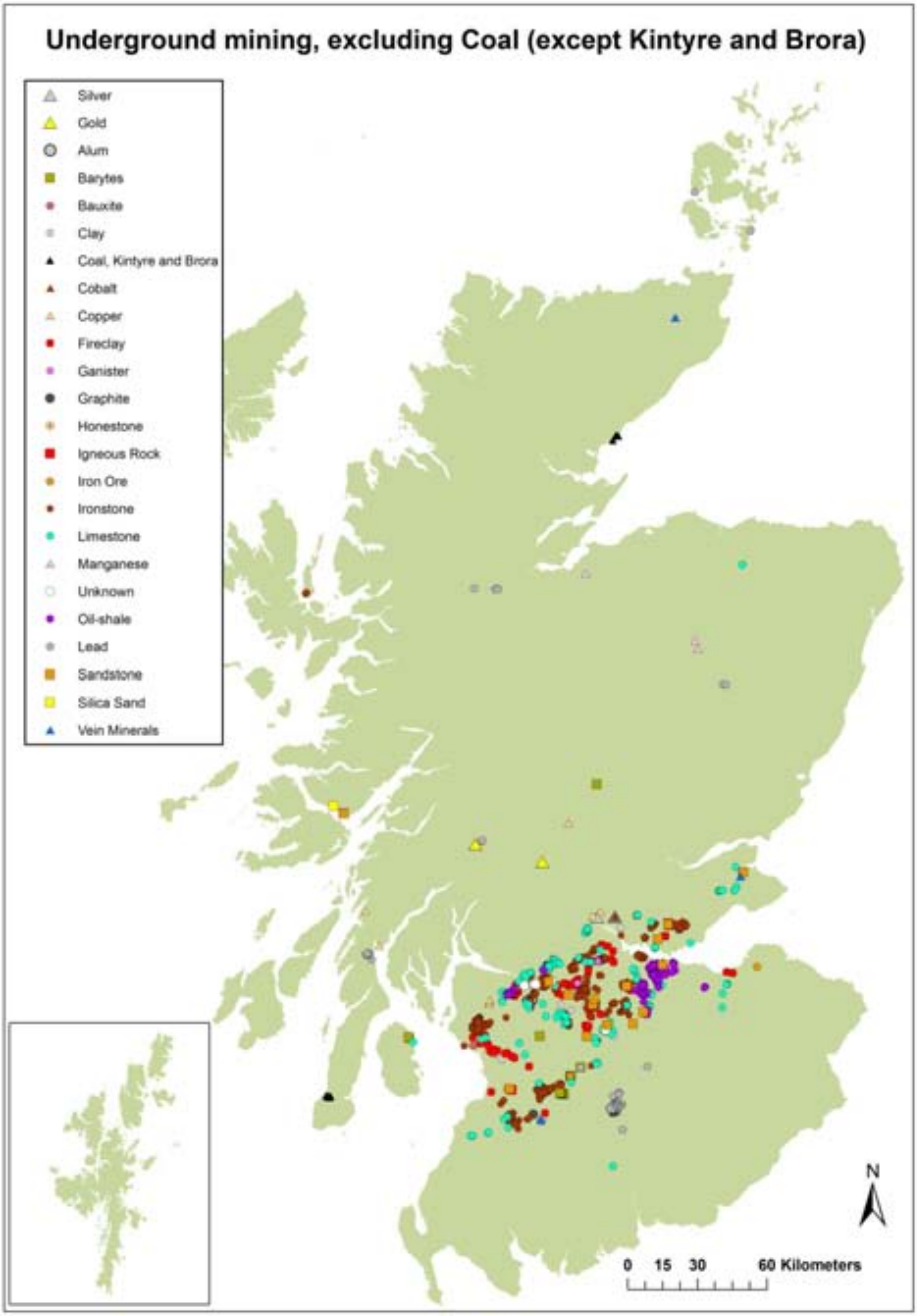


Figure 11 Localities recorded as mines in the BGS database of mines and quarries (BritPits – http://www.bgs.ac.uk/products/minerals/britpits.html). Excludes coal mines, except those in Kintyre and Brora.

6.2 PREVIOUS STUDIES AND EXISTING INSTALLATIONS

Previous UK studies include the Shawfair Minewater Project: Scottish National Mine Water Potential Study (PB Power, 2004; Appendix 1), BRE produced a report titled —Assessment of Mine water Potential in UK" in 2008 as part of the Mine water Project, which was supported by the Interreg NWE programme (Wiltshire and Burzynski, 2008).

The former study (PB Power, 2004) considered the largest 62 coal mines in Scotland, including those with gravity flows and those being pumped. Resource assessments mainly used the number of men that worked down the mine as a proxy for the volume of mine water that might be available. The study considered the potential for mine water heating at Shawfair, near Edinburgh, as part of a consideration of the wider potential across the Midland Valley of Scotland. PB Power (2004) calculated that mine waters could contribute up to 1,708 GWh per annum of heat, if grants were provided. This equates to about 3% of their estimate of Scotland's total annual heat demand in 2004.

BGS has recently funded an internal project to make a preliminary assessment of the heat potential that is accessible as a result of Glasgow's mining legacy (Campbell et al., 2010). The assessment particularly considered the flow paths created by the mining and the potential heat-in-place (Crane, et al., 2011, unpublished BGS report).

This assessment of the geothermal potential of mine water in Scotland draws on the recent BGS work, including 3D modelling, and utilises other available data to provide an estimate of potential borehole yields and the extent of the likely resource across the Scottish coalfields. The appraisal is based on the best estimates of geological and hydrogeological properties of the mined areas, providing a different viewpoint from the earlier studies. Ironstone and oil-shale mines within the Midland Valley may also provide local potential for mine water heat recovery.

There are two existing installations of GSHPs tapping mine water in Scotland: Shettleston in east Glasgow and Lumphinnans in Fife (Appendix 2):

i) Shettleston is a 100 m depth open loop ground source heat scheme completed in 1999 and serves 16 new-build dwellings; heat is also supplied by solar water heating and passive solar design (Sust.org, 2012).

ii) Lumphinnans is an open loop ground source heat scheme retro-fitted to a 1950s apartment block of 18 dwellings, completed in 2001. Mine water is pumped from flooded coal mine workings via a 172 m deep borehole. Banks et al. (2009) recorded that these were operating satisfactorily up to the time of reporting, although the Lumphinnans installation had suffered some vandalism which needed repair.

Operating mine water heat recovery schemes in Europe include Heerlen in the Netherlands (European Union, 2008; Roijen, 2011), Hunosa in northern Spain (Loredo et al., 2011) and Novoshaktinsk in Russia (http://www.netinform.net/KE/files/pdf/Novoshakhtinsk_PDD_ver01_Det.pdf).

Mine water heat recovery schemes are also planned at the National Coal Mining Museum in Wakefield (Faull, 2011) and in Stoke on Trent (http://www.stoke.gov.uk/ccm/content/council-and-democracy/communications/2012-press-releases/06-2012/134-12.en;jsessionid=aF5rFTMtHK76).

6.3 GEOLOGY AND MINING HISTORY

6.3.1 Coal, ironstone and oil-shale bearing strata

Coal-bearing sedimentary rocks of Carboniferous age are found in the Midland Valley of Scotland. The geology of the main coal- and ironstone-bearing strata is summarised in

Table 6; the table includes a column stating whether or not each formation is known to have been mined, and how many seams were mined in the main coalfield areas of the Midland Valley.

Coal, ironstone and oil-shale bearing strata of Scotland are mainly of Carboniferous age. These sedimentary rocks are widespread across the Midland Valley of Scotland (

Figure **12**). The sediments were deposited in sedimentary basin environments, with deep centres and shallow edges, forming rocks which vary considerably in thickness. For example, the Limestone Coal Formation ranges from less than 10 m thick in parts of Ayrshire to more than 550 m in the Clackmannan basin (Robins, 1990).

The sediments were mainly deposited in cycles, resulting in repeated layers of different composition: typically sandstones, siltstones and mudstones with beds of limestone, coal, fireclay and lesser amounts of ironstone and oil-shale. Each cycle can be up to about 30 m thick, but 10 m is more typical (Cameron and Stephenson, 1985). The thickness of coal seams varies, but beds of about 1 m thickness are common; some seams thicken to about 3 m in areas of greater deposition, and in some exceptional cases seams can reach 15 m thick (Rippon, 2002).

The names of the formations of interest can be confusing: the Scottish Upper Coal Measures Formation in fact contains little usable coal and was previously known as the —barren measures”; there is, however, coal in the Scottish Middle Coal Measures Formation and the Scottish Lower Coal Measures Formation. The Limestone Coal Formation contains little limestone, but does contain some of Scotland‘s most significant coal seams (Table 6).

The geological structure of the Midland Valley is complex, and discrete coal seams cannot necessarily be traced across large areas. Different numbers and thicknesses of seams were mined in different areas (Table 6).

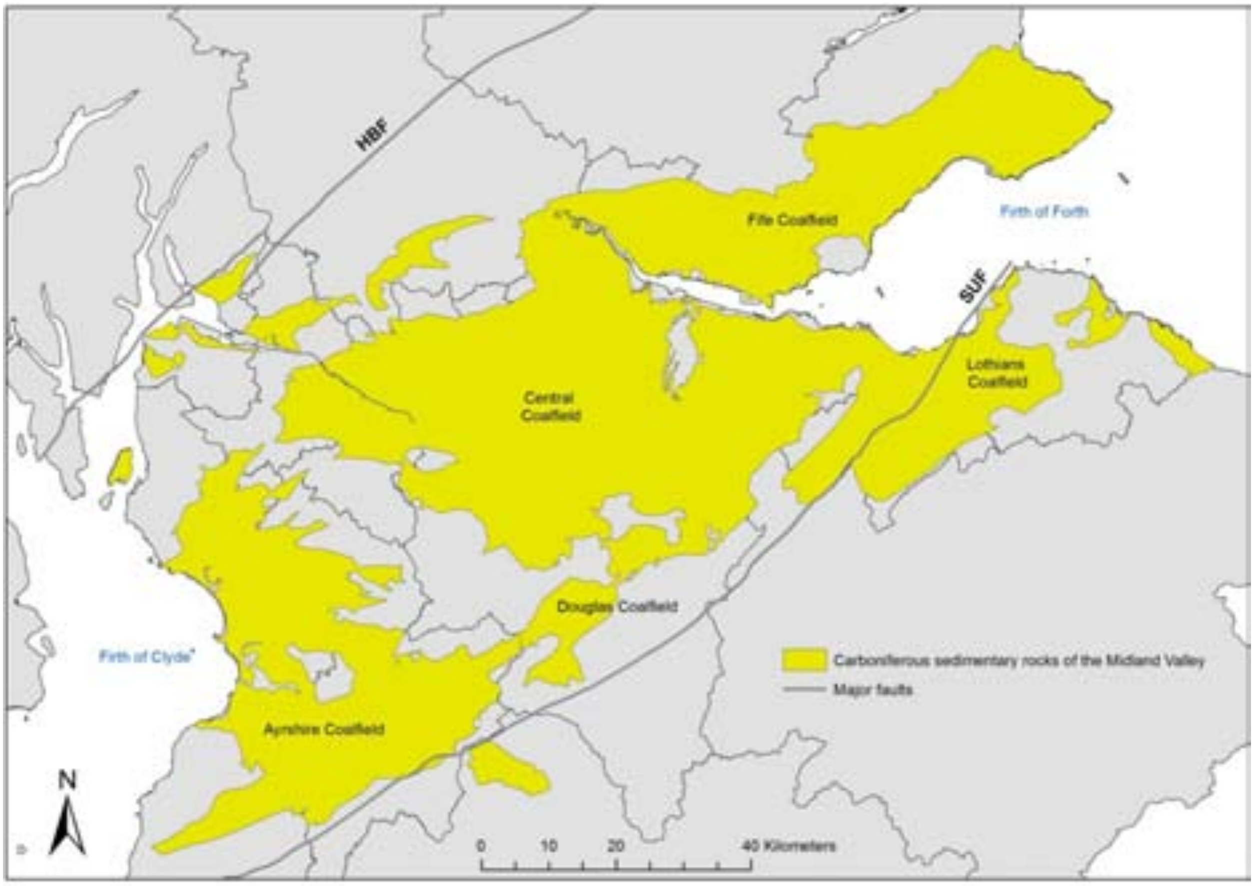


Figure 12 Carboniferous sedimentary rocks of the Midland Valley with main coalfields named.

Chrono stratigraphy		Lithostratigraphy		Lithological summary	Number of coal seams mined				
System	Series	Group	Formation		Ayrshire	Douglas	Central	Fife	Lothians
Carboniferous	Westphalian	Scottish Coal Measures	Scottish Upper Coal Measures Formation	Sandstone, siltstone, mudstone and seatearth in upward-fining successions. At least 750 m thick under the Firth of Forth and 560 m thick in Ayrshire, although not more than 300 m are preserved elsewhere onshore.	0	0	0	0	0
			Scottish Middle Coal Measures Formation	Upward-coarsening sequences of coal, siltstone, and sandstone predominate. Thickness varies: between 300 and 550 m in Fife and Lothian; as little as 150 m in North Ayrshire; over 600 m at New Cumnock	7	5	9	8	5
			Scottish Lower Coal Measures Formation		10	9	9	6	9
	Namurian	Clackmannan	Passage Formation	Fine- to coarse-grained sandstone with some quartz-pebble conglomerate, clayrock, seatearth and coal. Thickness varies from 10 m near Hamilton and parts of Ayrshire to 380 m in the Clackmannan basin.	1	0	0	0	0
			Upper Limestone Formation	Upward-coarsening sequences of mudstone, siltstone and fine- to medium-grained sandstone capped by seatearth and coal. Ranges in thickness from 10 m in parts of Ayrshire to 600 m in the Clackmannan basin, although to the east it is partly replaced by volcanic rocks.	4	3	0	1	1
			Limestone Coal Formation	Repeated successions of mudstone passing upwards into siltstone and fine- to medium-grained sandstone, then seatearth and coal. Virtually no limestone. Thickness ranges from less than 10 m in parts of Ayrshire to more than 550 m in the Clackmannan basin.	13	10	5	12	18
	Visean	Strathclyde	Lower Limestone Formation	Cyclic sequence of sandstone, mudstone, coal, and marine limestone.	0	0	0	0	0
	Tournasian	Inverclyde	West Lothian Oil Shale Formation; Clyde Plateau Volcanic Formation; Gullane Formation; Arthur's Seat Volcanic Formation	Sandstone, siltstone, mudstone, oil-shale and seatrock, with some coal seams, ironstone and limestone.	0	0	0	0	13*

Table 6 Geology of main coal bearing strata of the Midland Valley. See Figure 12 for locations of coalfields. * Refers to oil-shale seams in West Lothian.

6.3.2 Mining history

Coal mining has been an important part of the Scottish economy for many centuries, a consequence of the abundance of coal-bearing strata and range of coal types. There are records of coal mining activity in Scotland dating back to the 12th Century (Craig, 1991), although the scale of mining was very small until the late 16th Century.

Early underground workings were shallow and either dry or gravity drained. Such drains are likely to remain today, and thus the workings may still be dry. Production increased dramatically following the invention of pumping machinery, and particularly James Watt's improved steam engine of the late 18th Century (Craig, 1991). Dewatering of mines, by pumping to lower the water table, enabled mining in much deeper workings.

Stoop and room (also known as pillar and stall) mining, where stoops of rock are left unmined to support the roof of the mine (Figure 13), was the most common extraction technique in Scotland until the mid 20th Century (Younger et al., 2002).

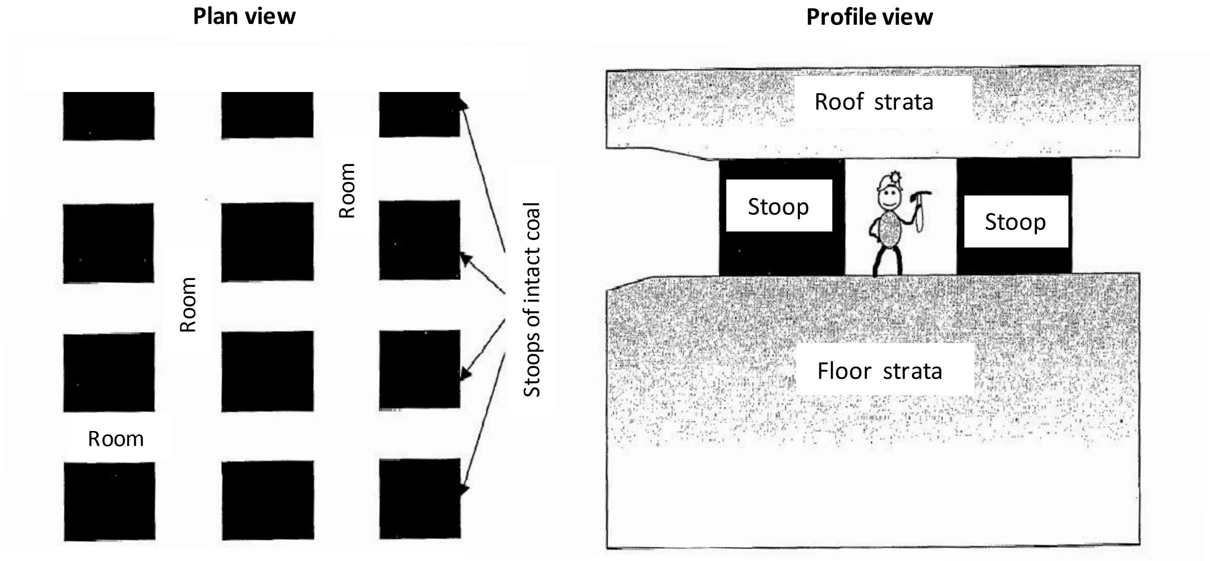


Figure 13 Layout of stoop and room mine workings. Plan view on left and profile view on right. (Younger and Adams, 1999).

Since the 1950s, most underground mining has used the longwall method of extraction (Rippon, 2002). In longwall mining the coal seam is worked between two parallel access roadways (Figure 14). A drum shearer breaks up the coal as it moves from the roadway at one side of the panel to the other. Moving roof supports protect the area directly adjacent to the coal face, but as the shearer advances (or retreats, depending on the system), the roof is allowed to collapse. The coal panel between the roadways is typically 100 to 250 m wide (Younger et al., 2002). Deep (underground) mining ceased in Scotland when Longannet Colliery closed in 2002 (Rippon, 2002).

On abandonment, pumping stopped in most mines and water levels have largely rebounded or are still rebounding. Pumping continues in a limited number of mines, to prevent or minimise surface discharges of poor quality water.

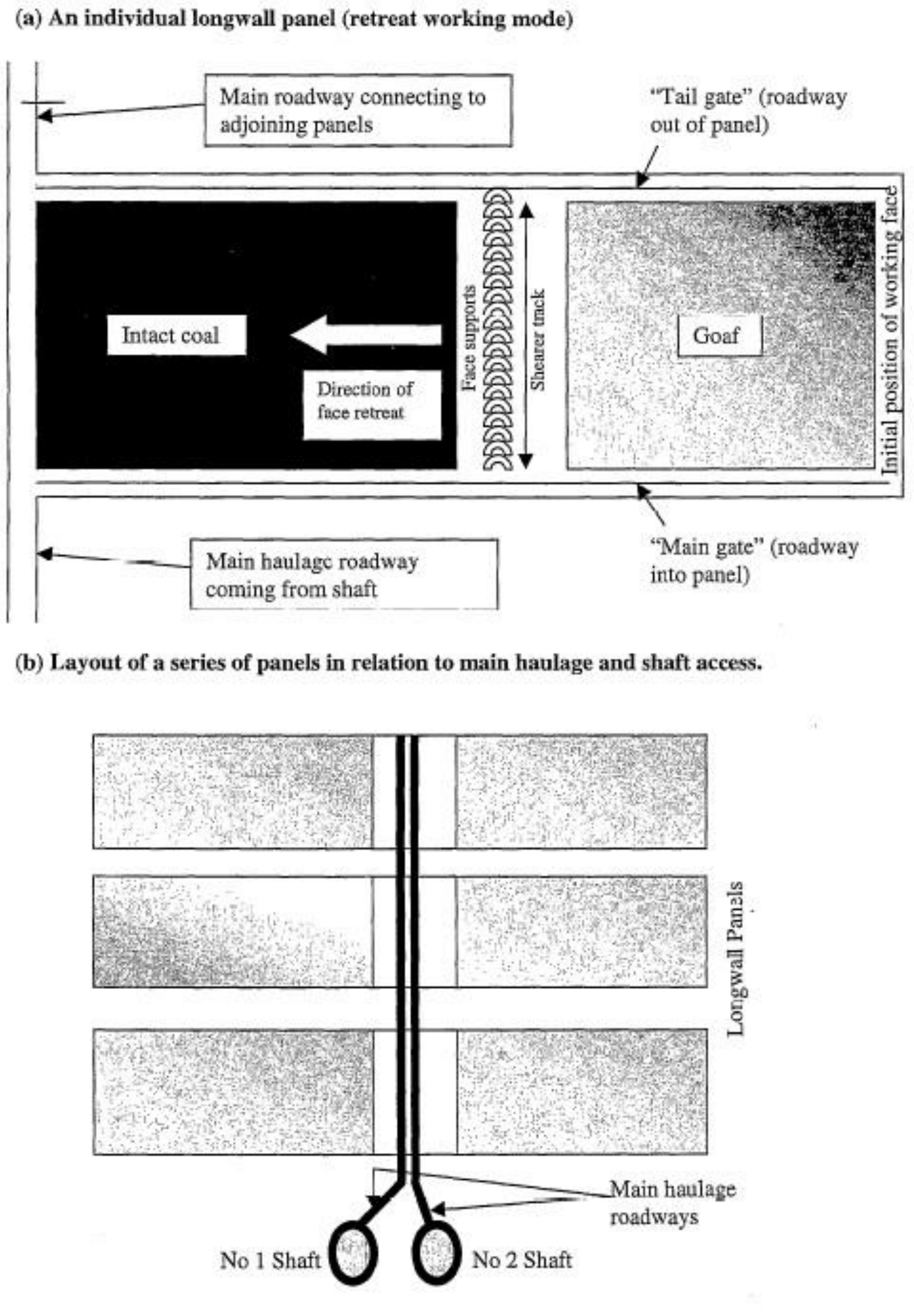


Figure 14 Layout of typical longwall mine workings (Younger and Adams, 1999).

Cannel coal (also known as boghead Coal and torbanite) was used to produce "Paraffin Oil" – the first plant in Britain to process mineral oil commercially was set up in Bathgate in 1851. It gave an oil yield of 535 to 580 litres/tonne, but the deposit was exhausted within 12 years. Around the same time oil-shale was discovered in West Lothian and identified as a raw material suitable for the production of shale-oil and replaced cannel coal in the retorting and refining processes.

West Lothian is unusual in the British Isles in having oil-shale seams that are thick and widely developed. Oil-shale mining reached its maximum productivity in the early years of the twentieth century, with outputs of more than three million tons of oil-shale. Although oil-shales are developed at over a dozen horizons within the West Lothian Oil-shale Formation, three multiple, thick shale units produced the bulk of the mined oil-shale: the Broxburn Shale, Dunnet Shale and Pumpherston Shale (Barron et al., 2006).

By 1950, production had declined to 740 943 tons produced at half a dozen mines and three opencast sites.

6.4 HYDROGEOLOGY OF ABANDONED MINES

Mining radically alters the hydrogeology of impacted areas, though the effects vary depending on factors such as the method of mining and the number and thickness of mined seams. The key impact is to increase the permeability of the strata above the mined horizon(s), making it easier to obtain usable yields of groundwater.

6.4.1 Open shafts, roadways and drifts

Many shafts, roadways and other linear access structures such as drifts (see Younger et al., 2002 for definitions) were built to last, and will remain as open voids in the subsurface today. Where these are beneath the water table and remain open they will be zones of extremely high permeability. They are typically interconnected, so large sustainable abstractions might be obtained.

6.4.2 Increased post-subsidence porosity and permeability

Detailed modelling and analysis of mine workings in the Glasgow region (Campbell et al., 2010; Crane et al., 2011, unpublished BGS report) indicated that stoop and room mining formed a relatively small proportion of the total mining. In stoop and room mining the roof is supported by pillars (stoops) of rock that are left in situ during mining operations (section 6.3.2). After mining work is complete, and assuming collapse has not taken place, the voids (rooms) occupy around 50% of the mine volume.

Longwall mining involves the removal of sequential strips of coal and associated collapse of the worked strips. On collapse, the voids are filled with broken overburden (called goaf or gob), and concomitant subsidence occurs at the surface. It has been estimated that about 20% of the mined void would remain after longwall mining-induced subsidence has occurred (Younger and Adams, 1999).

The mechanism of subsidence induced by longwall mining creates stresses in the overlying strata which have been well studied and are summarised in Figure 15. Applying this model to typical longwall panel widths (W) of 100 to 250 metres indicates that some 40 to 100 metres of strata above the mined seam will be fractured due to the subsidence; this volume of rock therefore has enhanced permeability (Younger and Adams, 1999). Thinner zones above this will be affected by compression and extension (Figure 15).

The mined horizon is likely to remain the most permeable zone even though, post-subsidence, it contains broken goaf. Younger and Adams (1999) suggested that this will have a similar porosity to gravel, about 0.3, or 30%.

The goaf horizon will be dominated by intergranular (between particles) flow, while fracture flow will dominate in the disturbed zone above. It is common for multiple seams at different depths to be mined, creating a ‗clubsandwich' effect of layers with different degrees and types of permeability. Overall, fracture flow is likely to dominate.

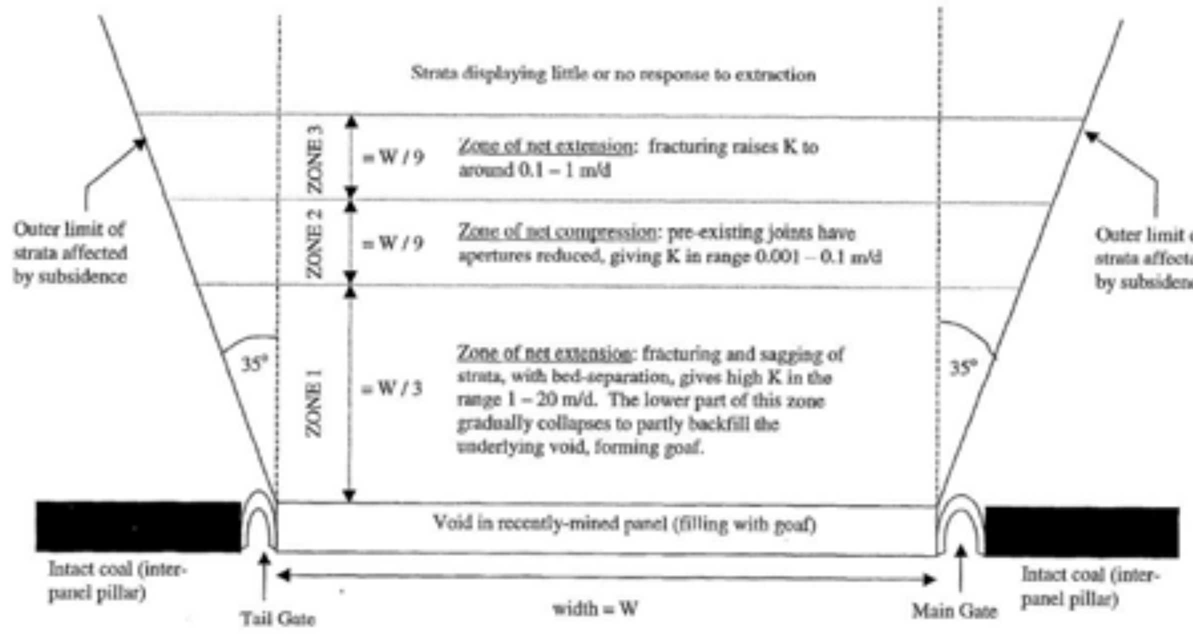


Figure 15 Schematic diagram of the zones of extraction-related subsidence above a recently worked longwall panel (Younger and Adams, 1999).

Unmined coal-bearing Carboniferous strata tend to form complex, multi-layered minor aquifers, with vertical and lateral variations – low permeability layers (of mudstone and other relatively impermeable rocks) interbedded with layers of more permeable sandstone or limestone. Intrusions of igneous rock (dykes, sills, plugs) and faults can also compartmentalise these aquifers. When mining has occurred the resulting —anthropogenically enhanced aquifer" (term coined by Banks, 1997) is also multi-layered and certainly complex, but with a generally higher permeability enabling larger yields to be obtained.

One advantage of the multi-layered nature of these mining-enhanced aquifers is the potential to abstract water from one depth interval and re-inject the used water at lower temperature to a different horizon. This is beneficial as obtaining consent to discharge mine water to surface or sewers is likely to be difficult, plus this type of circulating system maintains water levels in the subsurface while providing a hydraulic and thermal barrier (by intervening low permeability strata) which increases the time for thermal breakthrough (thermal —short-circuiting") to occur. The Shettleston scheme in Glasgow was designed in this way.

6.4.3 Water chemistry

Water from abandoned mines is often of poor quality due to its chemical composition, and it can cause a range of environmental problems. A comprehensive description of the various issues and their occurrence in the UK is given by the Environment Agency, the Scottish Environment Protection Agency and the Coal Authority in their joint report, —Abandoned mines and the water environment" (Johnston et al., 2008).

Problems include low oxygen, acidic waters, which can have high concentrations of dissolved metals like iron which precipitate out when exposed to oxygen as the water is brought to the surface. Iron oxide flocculants have negative impacts; for example, making it difficult to re-inject water because the particles clog the voids in the subsurface, thereby reducing permeability.

Available technologies mean these issues need not prevent the water being used for GSHP, but the water chemistry must be tested and any problems accounted for in the design of the system. There is the potential for water to be treated following heat extraction and prior to re-insertion. The Coal Authority operates a pilot treatment and re-insertion scheme at Dawdon in County Durham and treatment and re-insertion issues have been addressed at the Heerlen scheme in the Netherlands (European Union, 2008).

6.5 DATA AND INFORMATION AVAILABILITY FOR SCOTLAND

6.5.1 Areal and vertical extent of mining

The Coal Authority holds the most comprehensive data describing the mining history of Scotland, with a large amount of data digitised for use in GIS. This includes 33 936 underground working polygons (with associated depth, date and seam extraction data) in 5 seams, 2,785 probable unrecorded working polygons (and associated depth), and 11 637 spine roadways (underground roadways connecting coal etc workings). Handling this large volume of spatial data is outside the scope of this project.

BGS also holds a large amount of information about mines; for example, the 1980s Environmental Geology Map (EGM) series covers the Midland Valley of Scotland at 1:10 000 scale. The series includes locations of known adits and shafts in mined areas. The EGMs are available as georeferenced, scanned images, but the information within them is not digitised except in the Glasgow area, for full use in a GIS. (http://www.bgs.ac.uk/discoverymetadata/13603135.html).

For this study, the most appropriate data on the areal extent of mining in Scotland was deemed to be the Coal Authority‘s polygon showing where a more detailed search of mine plans should be made when considering development (Figure 16).

The vertical (depth) extent of mining in Scotland was calculated by generating a surface indicating the depth of mine workings across the Midland Valley. This was created using a dataset of all records in the BGS Single Onshore Borehole Index (SOBI: http://www.bgs.ac.uk/products/onshore/SOBI.html) that contained the word ‗shaft‘ or ‗pit‘. These data were then filtered to remove those with a ‗0‘ start height, a ‗0‘ borehole length or those which started below ground level (Figure 17). The surface was created by interpolation in GOCAD® software, and is displayed in Figure 18 to Figure 21. The volume of the mine-worked area (i.e. from the base of the mine workings to land surface) is estimated therefore to be 6 x 10^{11} m^3, or 600 km^3.

For more detailed studies, it would be necessary to have data on the number and thickness of seams mined (cf Campbell, 2010), and of the locations of shafts and roadways in the vicinity. BGS has already compiled much of this information for Glasgow (Campbell, 2010; Figure 22). Data for other parts of the Midland Valley are available digitally from the Coal Authority, or in paper or scanned image form from BGS.

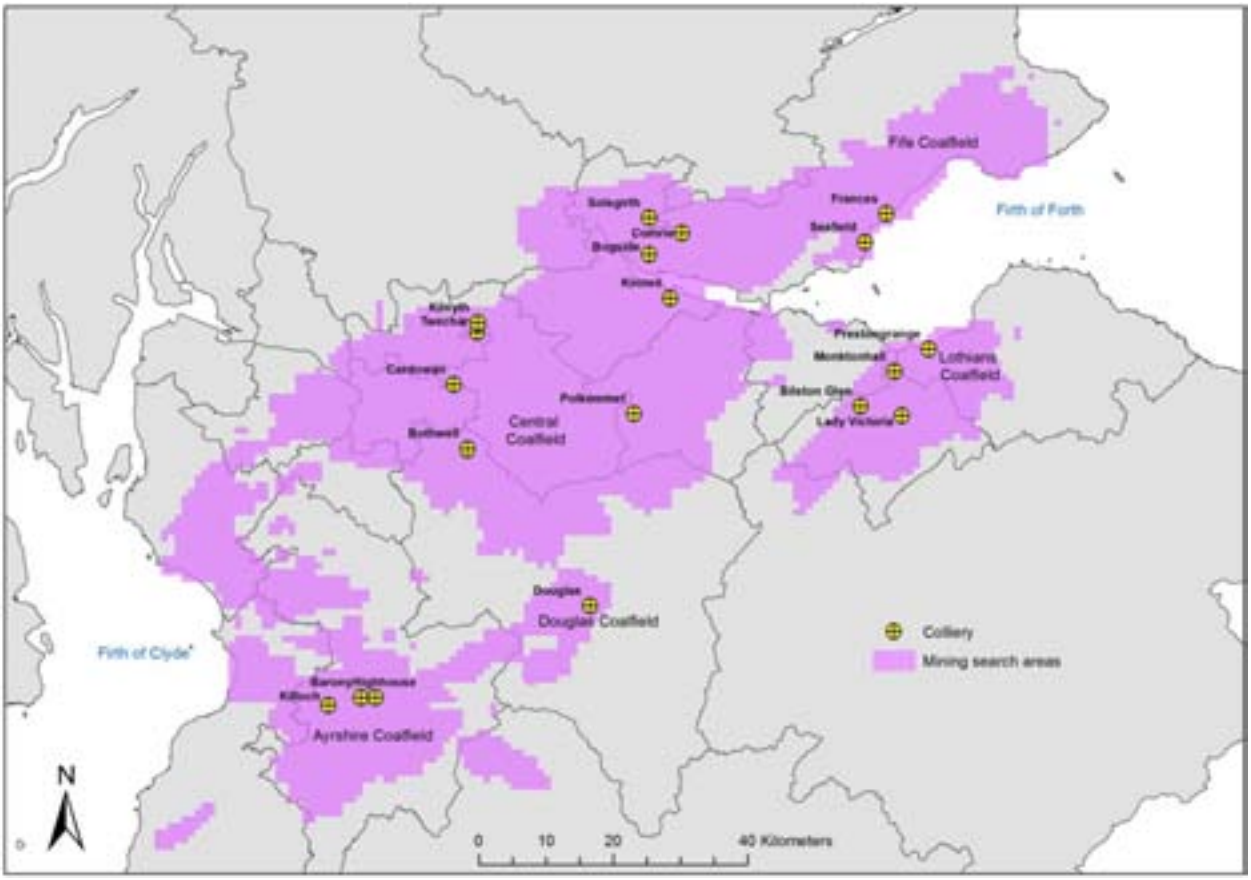


Figure 16 Coal Authority mining search areas and locations of Midland Valley collieries listed in Table 8 and Table 9.

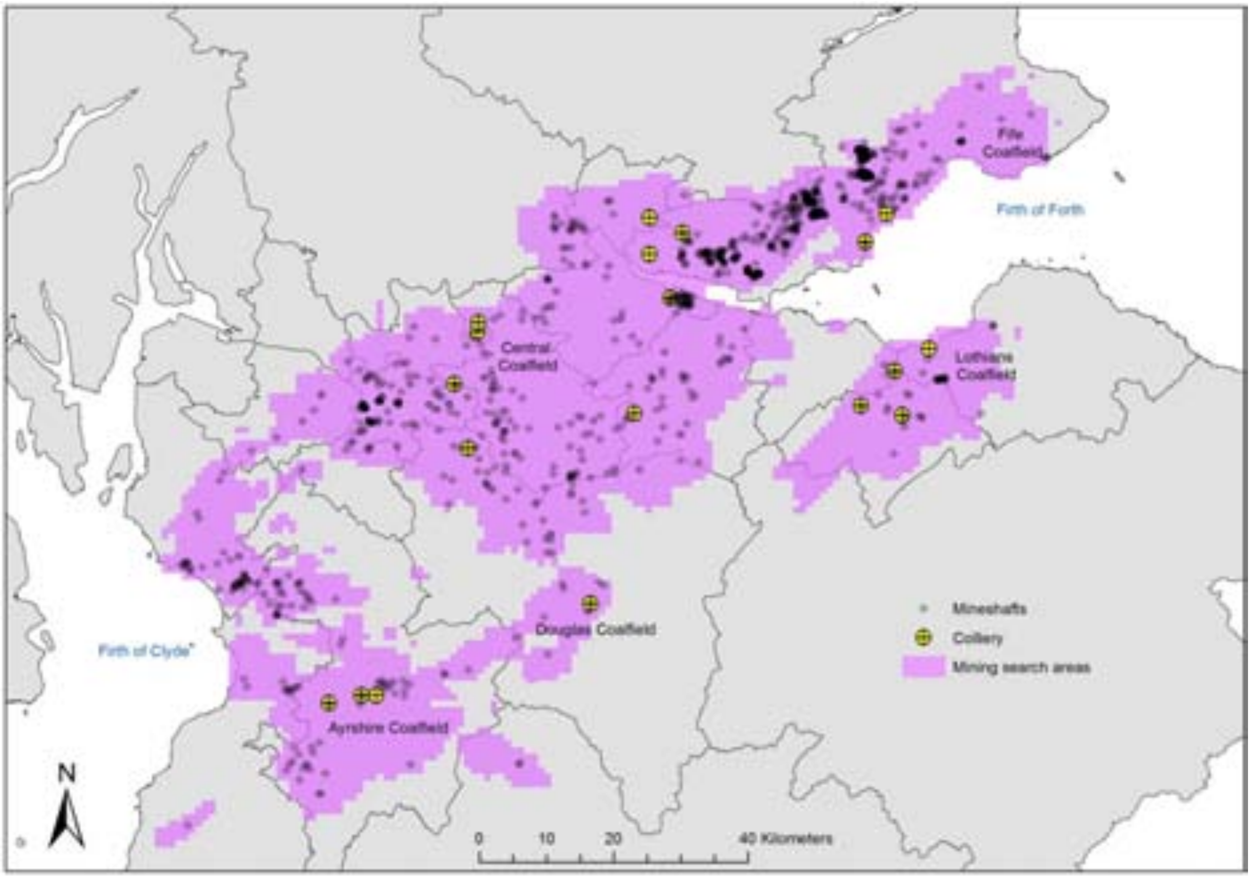


Figure 17 Mineshafts in the Midland Valley.

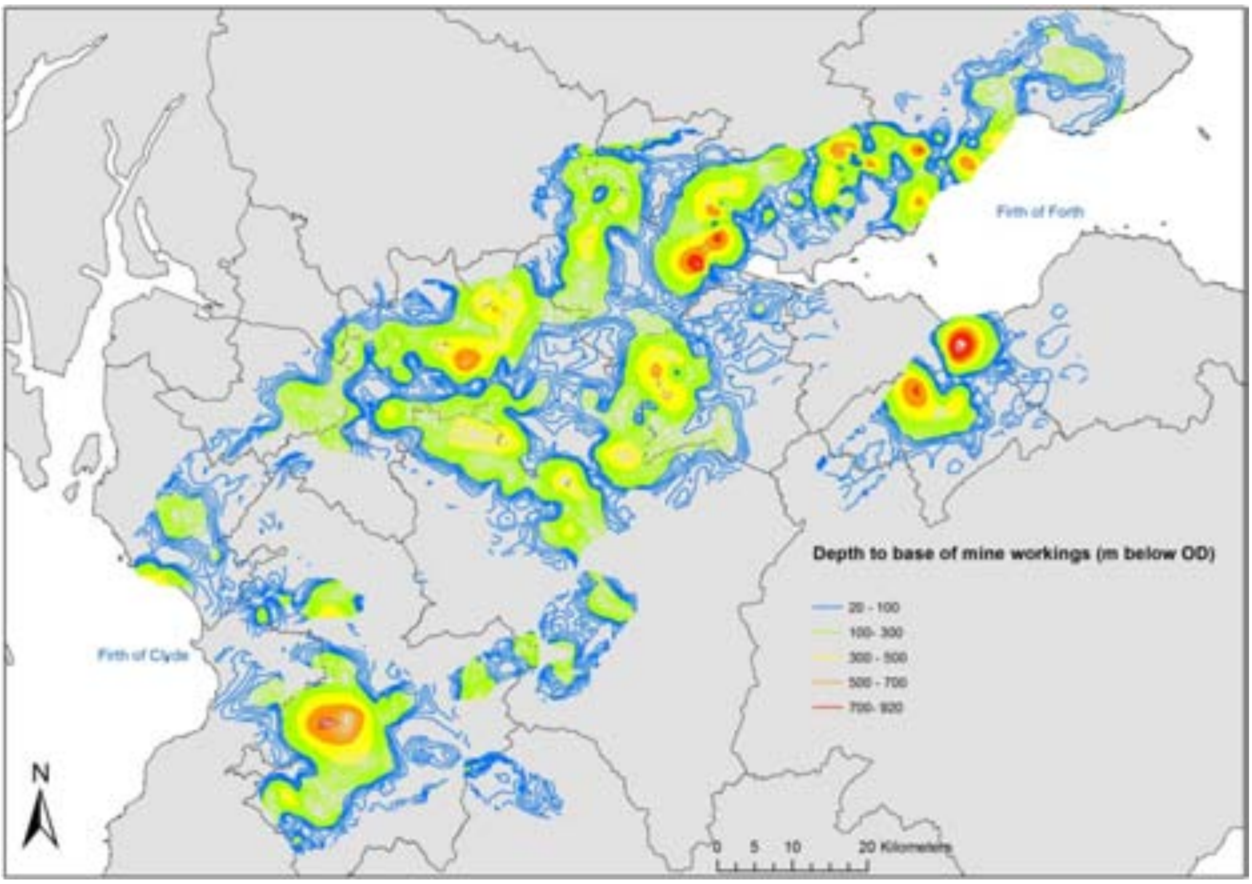


Figure 18 Depth of mine workings (interpolated from SOBI data), showing deepest workings in orange and red.

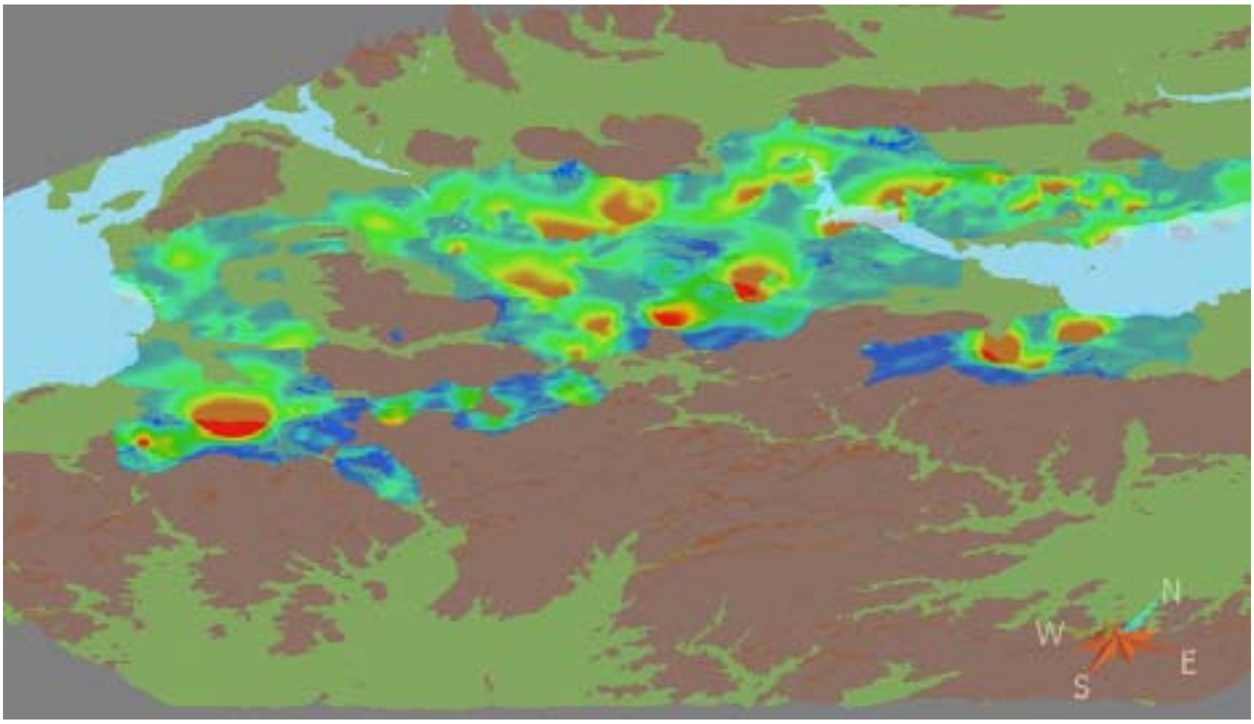


Figure 19 Depth of mine workings viewed in GOCAD® (©Paradigm) 3D modelling software, showing deepest workings in orange and red.

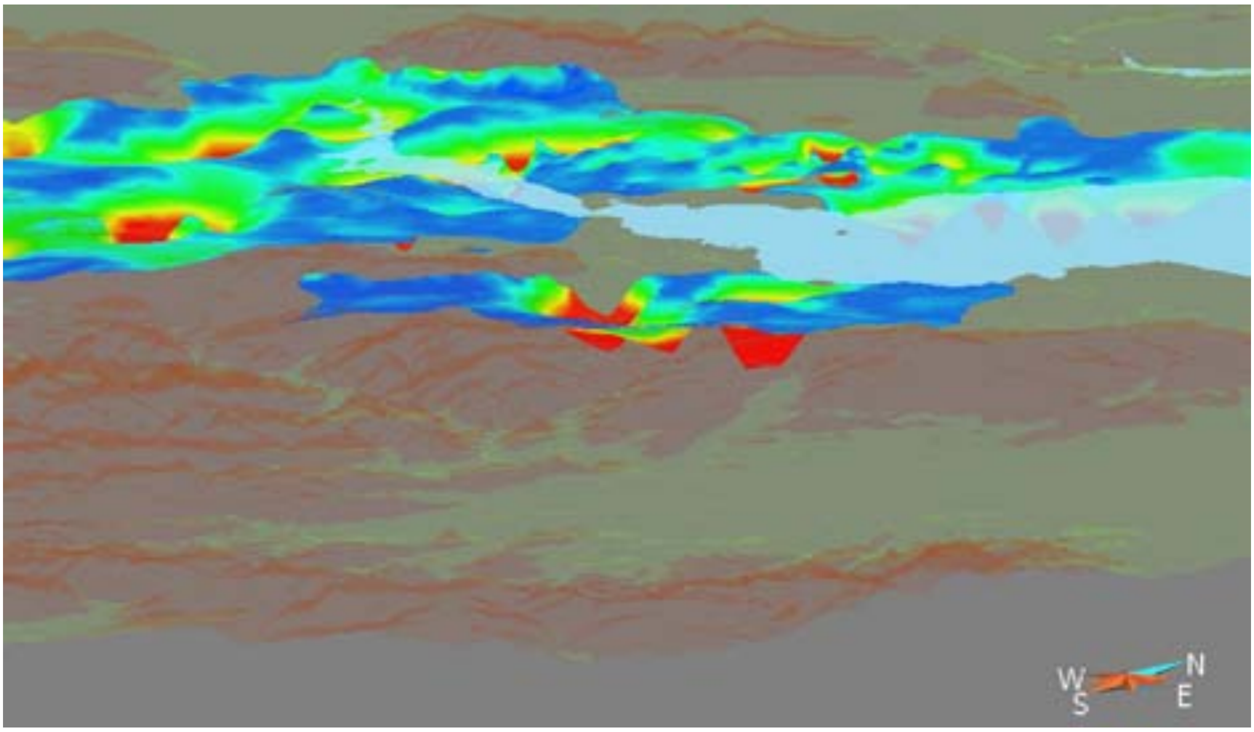


Figure 20 Depth of mine workings in the Lothians, Fife and Central coalfields, viewed in GOCAD® (©Paradigm) 3D modelling software and showing deepest workings in orange and red.

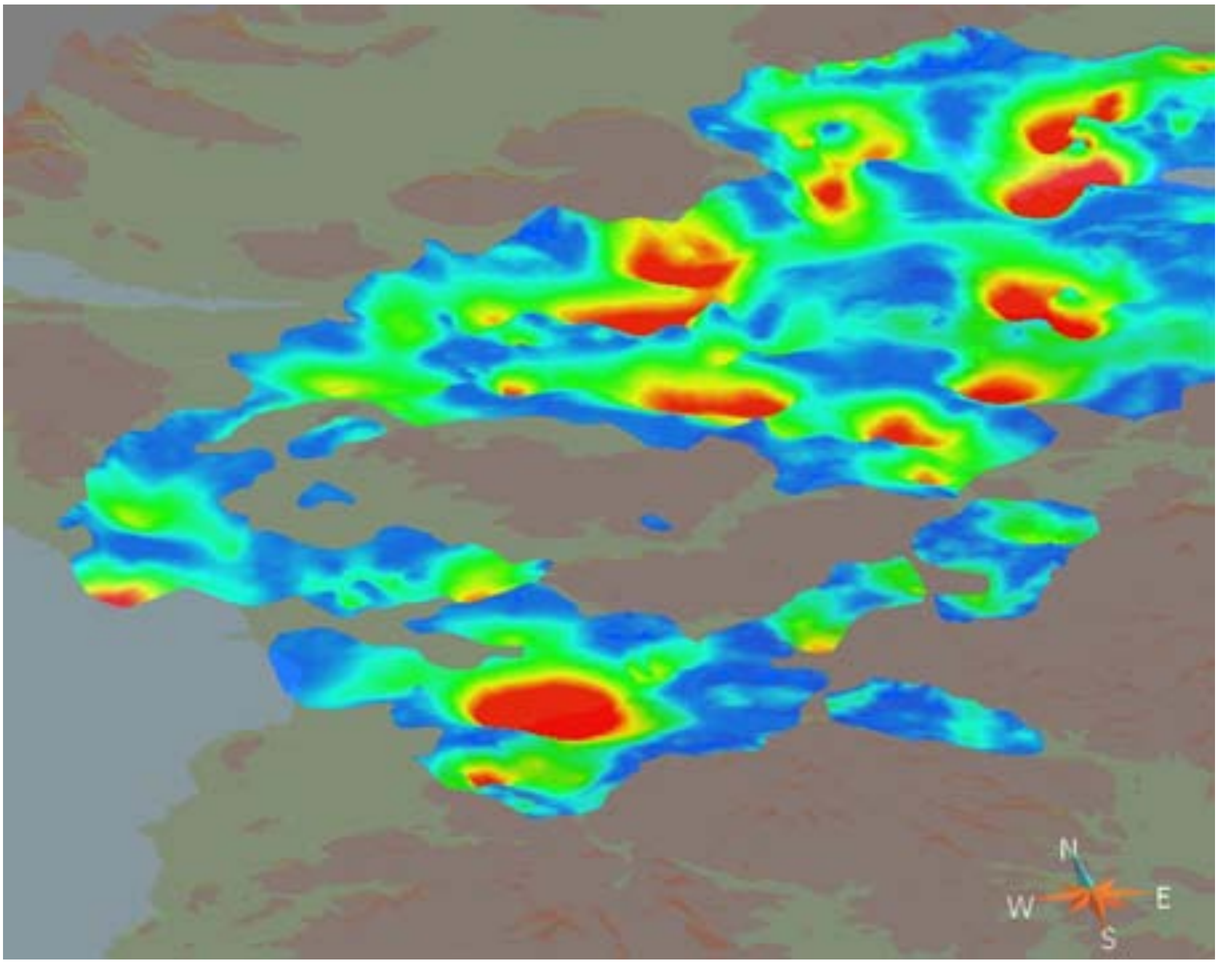


Figure 21 Depth of mine workings in the Ayrshire, Douglas and Central coalfields, viewed in GOCAD® (©Paradigm) 3D modelling software and showing deepest workings in orange and red.

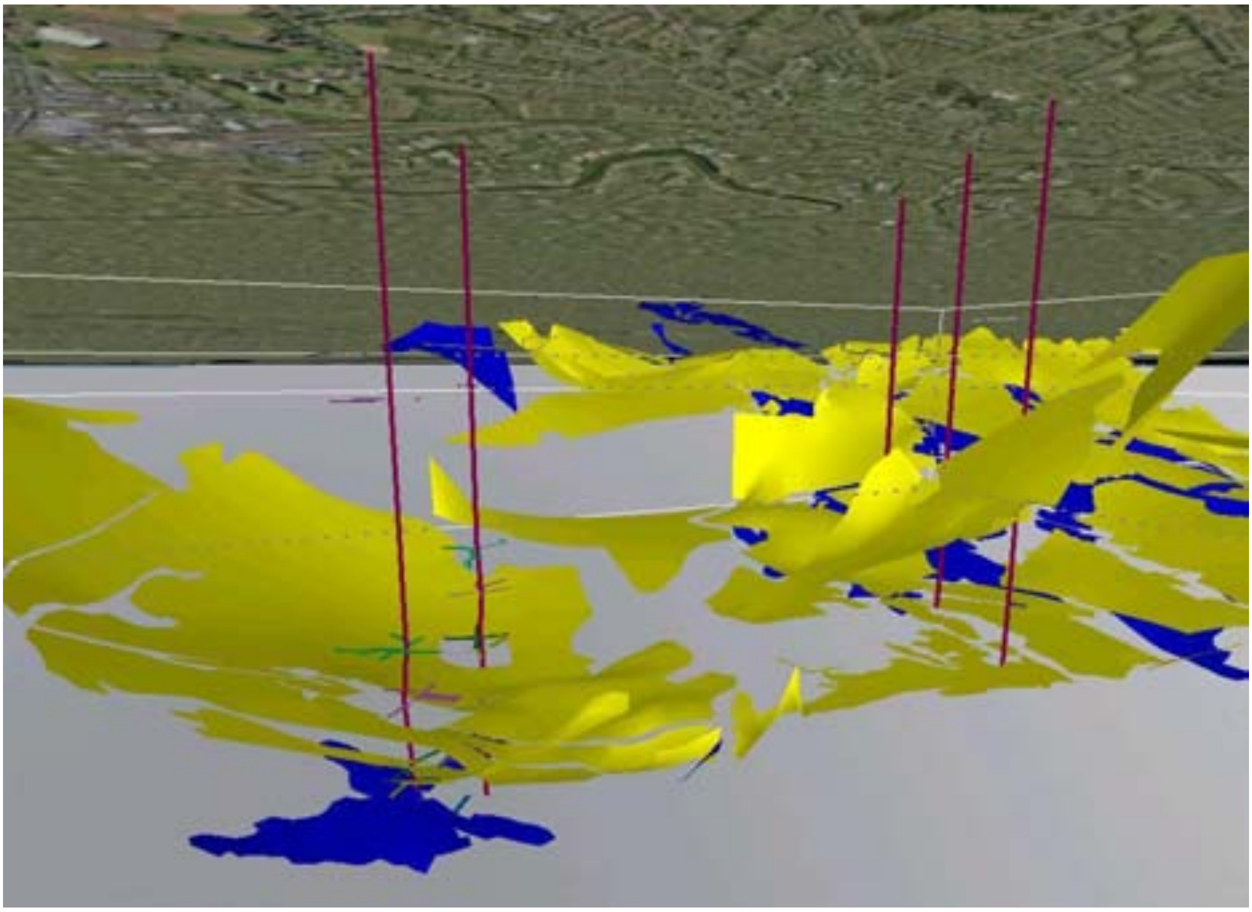


Figure 22 3D model of mined coal seams (yellow and blue surfaces), mine shafts (red sticks) and mine roadways (green, light blue and pink), beneath Glasgow's East End. Viewed in Virtalis/BGS GeoVisionary software.

6.5.2 Porosity, hydraulic conductivity and connectivity

The additional porosity created by mining beneath a 5 km x 5 km square of Glasgow (NS66SW) was calculated utilising data relating to the number and thickness of mined seams (and taking into account the expected proportion of mined void to remain post-collapse) that were collated and digitised for the Glasgow 3D geological model (Crane et al., 2011, unpublished BGS report). The calculated increase in porosity for this block of rock is only about 0.14%, compared to an average porosity for the Scottish Coal Measures of about 10%. However, the increase in porosity will not be evenly distributed throughout the body of rock and, locally, will increase by more than this.

More importantly, the permeability will have been increased by orders of magnitude due to mining activities. This will enable pumping at much higher rates than in undisturbed strata.

A prime target for a scheme would be shafts and roadways (Figure 23), as these will have permeability that is orders of magnitude higher than the surrounding disturbed strata. Data on the location of these can be obtained from the Coal Authority. Due to the volume of data, these were not used for this and for this national-scale study, but they would be important for site-specific investigations.

Figure 23 Monktonhall Colliery Underground Roadway: view looking along an underground roadway at Monktonhall Colliery, Midlothian, 1970s. This colliery produced coal from 1967 to 1997. Image courtesy of the Scottish Mining Museum.

6.5.3 Energy/Heat

The two key parameters which influence the potential for getting heat from mine waters are the flow rate at which water can be abstracted from the subsurface without significantly depleting the resource at the site in question, and the temperature of that water.

It is very difficult to predict the likely flow rate (usually referred to as the borehole yield) that a particular borehole might obtain due to the great variability in mining-enhanced aquifers, but an analysis of available data enables us to establish a typical range of yield. It should be borne in mind though that very low-yielding boreholes are often not recorded, leading to data sets biased towards higher yields.

Available data for yields from the Carboniferous strata of the Midland Valley are collated in Table 7, organised according to the geological formation from which the yield is believed to be obtained. The final column notes whether the yield is clearly associated with mines. Examples of dewatering yields are given in Table 8.

In general, it is thought reasonable to expect a yield of about 10 l/s in mining-enhanced aquifers, from a borehole penetrating a reasonable saturated thickness of strata (minimum of 50 metres). For the purposes of the calculations of potential heat abstraction, a range of 5 to 25 l/s per borehole seems reasonable.

It is worth noting that vast volumes of water were pumped from mines during operation to maintain the water level below the working zone. The pumping rates did vary significantly: the examples given in Table 8 range from 13 l/s to 315 l/s. These values cannot be applied directly to the current study, but do give an insight into the amount of recharge that must have been occurring to require such high volumes to be pumped.

Group	Formation (Fm)	Yield	Location	Associated with mines?
Scottish Coal Measures Group	Scottish Middle and Scottish Lower Coal Measures formations	up to 150 l/s from some working coal mines	Southern Midland Valley, east of Lanark	Yes
		2 to 5 l/s	Southern Midland Valley, east of Lanark	No
		75 l/s from 194 m borehole	Inveresk Paper Mills, Musselburgh	Yes
		Many of the coal mines pumped water for drainage purposes at rates of up to 75 l/s	Southern Midland Valley, west of Lanark	Yes
		Single borehole yields of 5 l/s are more typical	Southern Midland Valley, west of Lanark	No
Clackmannan Group	Passage Formation	Supports several moderate-yielding boreholes (up to 20 l/s)	Fife and Kinross	No
Strathclyde Group Inverclyde Group	Upper Limestone Formation Limestone Coal Formation Lower Limestone Formation	Up to 30 l/s from old mine shafts and adits	Fife and Kinross	Yes
		Dewatering at 40 – 75 l/s over 140 hours per week from 165 m and 225 m	Prestongrange Colliery (NT 373 737), from the Limestone Coal Fm	Yes
		1.5 l/s from 9 m borehole	Longniddry (NT 438 765)	Probably not
		650 m^3/d (7.5 l/s)	Pencaitland, from the Limestone Coal	Not stated
		2 l/s from a 70 m borehole	Upper Limestone Fm at Loanhead (NT 292 661)	Probably not
		1 l/s typical yield	Southern Midland Valley, west of Lanark	Probably not
		5 Ml/d (60 l/s) from a well field drawing from the Upper Limestone Formation. Exceptional yields included: 30 l/s for 10 m drawdown, 15 l/s for 20 m drawdown, 1 l/s for 8 m drawdown.	Denny. Boreholes 48 to 85 m deep; deeper boreholes had better yields, probably due to contact with mine workings.	Very likely in the deeper holes.
		Typically small yields from Upper Limestone and Limestone Coal	Glasgow vicinity	No
		Up to 10 l/s where mine workings intercepted	Glasgow vicinity	Yes
		25 l/s	Parkhead [NS 624 647]	Yes
		14 l/s	Coatbridge [NS 752 642]	Yes
		9 l/s drawn from old workings	Netherfield (NS 618 647)	Yes
		One 198 m deep borehole yielded 9 l/s for 9 m drawdown, but 3 adjacent holes provided negligible yield	Glasgow Garden Festival site, Govan (198 m hole at 5668 6475)	Possibly
		Yields typically <0.5 l/s, rarely reaching 2 l/s	Southern Midland Valley, west of Lanark	Probably not

Table 7 Borehole yields (information from Robins, 1990; Hall et al., 1998; McAdam and Tulloch, 1985; Forsyth et al., 1996).

Dewatering rate	Location	Stratigraphical unit(s)
40 – 75 l/s over 140 h week from 165 m and 225 m	Prestongrange Colliery [NT 373 737]	Limestone Coal Fm
230 l/s constantly from 396 m depth	Bothwell Colliery [686 588]	Scottish Middle Coal Measures Formation
150 l/s from 206 m depth	Kilsyth Colliery [715 779]	Limestone Coal Fm
13 l/s for 12 hours per day from 317 m depth	Twechar Colliery [701 762]	Limestone Coal Fm
30 to 55 l/s	Typical dewatering rates for mines in the Falkirk District	Limestone Coal Fm and/or Coal Measures
35 l/s (Coal Authority pumping station; Parker, 2011)	Monktonhall Colliery, Midlothian	Limestone Coal Fm
75 l/s (Coal Authority pumping station; Parker, 2011)	Polkemmet Colliery, West Lothian	Scottish Lower Coal Measures Formation
120 l/s (Coal Authority pumping station; Parker, 2011)	Frances Colliery, Fife	Scottish Middle Coal Measures Formation, Scottish Lower Coal Measures Formation
315 l/s (Coal Authority pumping station; Parker, 2011)	Blindwells Colliery, East Lothian	Limestone Coal Fm

Table 8 Historical mine dewatering rates (information from Robins, 1990; Forsyth et al., 1996; Cameron et al., 1998; Parker, 2011.)

6.5.4 Recharge

It is assumed that mine water GSHP schemes will use a recirculation model to avoid the various issues associated with discharging to surface or mains, thus it is not necessary to know the natural recharge rate. As discussed above (section 6.5.3), the large volumes of water removed during active dewatering of mines indicates that significant recharge does occur in these areas.

6.5.5 Groundwater levels

For this national-scale study, groundwater levels were not modelled (assumed full thickness saturated); however, a site-specific study would need to obtain recent water-level data to ensure that an adequate saturated thickness of aquifer is present in the horizon to be targeted as part of a feasibility study.

6.5.6 Temperature of mine waters

The temperature of mine waters generally increases with depth according to the geothermal gradient (see Part 1 of this report, and in particular section 2.1.3). It is not simple, however, to predict the temperature of water pumped from a borehole, as water of different temperature may be entering the borehole at different depths. Groundwater exchanges heat with the rocks it flows through but the degree of equilibration will depend on the rate of groundwater flow through the aquifer.

A compilation of mine water temperatures for boreholes in the Midland Valley shows a fairly narrow spread of temperatures (Table 9). The data in the table have been sorted by depth, but this shows no correlation to the observed water temperature. Mine water temperatures range from 12 to 21°C, with a mean (and median) of 17°C.

Borehole name	Grid reference	Depth (m)	Temperature (deg C)
Douglas Colliery	NS 830 300	239	12.2
Bogside Colliery	NS 9564 8778	334	17
Solsgirth Colliery	NS 9777 9329	387	21.5
Barony Colliery	NS 5105 1971	411	17
Highhouse Colliery	NS 5321 7202	436	18
Polkemmet Colliery	NS 9190 6278	549	17
Killoch Colliery	NS 4883 2130	655	17
Bilston Glen Colliery	NT 2996 6320	670	15
Lady Victoria Colliery	NT 3294 6666	768	18

Table 9 Mine water temperatures for boreholes in the Midland Valley (extracted from Table **4**)

Robins (1990) stated that ―The temperature of groundwater circulating at shallow depths in Scotland generally ranges from 8 to 12˚C".

6.5.7 Mine water chemistry

On the whole, the quality of the water does not impact on GSHP schemes as long as the system installed is designed appropriately (section 6.4.3). Water chemistry therefore is not considered in this study. Published data are available and should be considered for site-specific situations.

6.6 METHODOLOGY

Two methods for estimating the low-enthalpy geothermal resource for a site or an area are considered here. Firstly, the total resource, or ‗heat-in-place', can be estimated for a body of rock. This, however, will always be many times larger than the potentially exploitable resource, which is dependent on many factors – hydrogeology, amount of heat in the system, pumping rate, re-injection potential, efficiency of heat extraction, economic considerations, etc. Secondly, the rate of heat output can be estimated based on estimates of sustainable abstraction rates and likely groundwater temperatures (‗flow rate method').

6.6.1 "Heat in place" estimate for mined areas

Geothermal resource estimates were made for the UK in the 1980s using an approach which calculated the heat resource in both the groundwater and the matrix (Downing and Gray, 1986). The Geothermal Resource is calculated using the full equation:

$H_0 = [\Phi\rho_w c_w + (1 - \Phi)\rho_m c_m]V(\theta_m - \theta_g)$ joules

where :

H_0 = the [total] Geothermal Resource, i.e. the total heat contained in the aquifer (joules)

Φ = porosity

ρ_w and ρ_m = densities of water and matrix respectively in g/m^3

c_w and c_m = specific heats of water and matrix respectively in J/g/°C

V = volume of aquifer in m^3

θ_m = mean reservoir temperature in °C

θ_g = mean annual ground temperature in ^oC.

Then, a maximum recovery factor is applied to assess the proportion of the total which may be available for development; the Identified Resource. This is more favourable when the cooled water is re-injected to the aquifer via a separate borehole (a doublet system) as opposed to when the water is dumped: when a doublet system is used, more heat is recovered from the aquifer by the re-injected water. The maximum recovery factor is defined by Lavigne (1978) as:

$[(\theta_m - \theta_{rej})/(\theta_m - \theta_g)]\ F$

where:

F is a factor related to the hydraulic properties of the aquifer and to the method of abstraction.

From experience in the Dogger aquifer in France, where water is re-injected into the aquifer using a doublet system, F = 0.33. In calculating the Identified Resource for the UK, an F value of 0.25 was used for a theoretical doublet system and 0.1 for a single well where rejected brine is disposed of subsequent to heat extraction. These values are best estimates and need to be tested through further research and practical experience. However they do provide relative estimates for comparison.

6.6.2 Flow rate method

The standard methodology for considering the potential output of an open-loop ground source heat system is described by Banks (2008). The calculation includes the anticipated groundwater flow rate from the borehole(s) feeding the system; here termed the ―flow rate method". The flow rate is multiplied by the specific heat capacity of water and the temperature drop in the water across the heat pump:

$$G = Z \,.\, \Delta\Theta \,.\, S_{VCwat}$$

Where:

G is the ground source heat (heat extracted from the ground) (W)

Z is the flow rate from the borehole(s) supplying the heat pump ($L\ s^{-1}$)

$\Delta\Theta$ is the temperature drop across the heat pump (˚K). For example, if groundwater is abstracted at 12°C and returned to the aquifer at 7°C, $\Delta\Theta$ would be 5°C (1°C is equivalent to 1°K).

S_{VCwat} is the specific heat capacity of water, 4180 $J\ K^{-1}\ L^{-1}$ (joules per degree Kelvin per litre).

This calculation gives a value for the ground source heat output in watts (joules per second).

6.7 CALCULATIONS/RESULTS

6.7.1 Heat in place estimate for the mined areas of the Midland Valley of Scotland

The heat resource in a body of rock can be simply calculated to provide an ‗order of magnitude' estimate. Recovery of this energy will depend on a wide range of factors but the figure is useful in relation to the calculated demand density. The calculation is based on many assumptions of variables, but these are clearly stated and can be changed if more accurate data become available.

6.7.2 Geothermal Resource of the mined areas of the Midland Valley

Assuming the average surface temperature is 10°C and there is an average geothermal gradient in the Midland Valley of 30°C /km (section 4.2.1 and Figure 6), then the temperature at 200 m depth will be about 16°C and the temperature at 500 m will be about 25°C. Assuming heat is abstracted from pumped groundwater and a drop of 10°C (replacing the temperature difference between mean aquifer and surface temperature in the calculation) is applied to the whole block then the potential Geothermal Resource is calculated as follows:

$H_0 = [\Phi\rho_w c_w + (1 – \Phi)\ \rho_m c_m]V(\theta_m - \theta_g)$ joules

where:

H_0 = the [total] Geothermal Resource, i.e. the total heat contained in the aquifer (joules)

Φ = porosity (0.1)

ρ_w and ρ_m = densities of water (1×10^6 g/m^3) and matrix (2.5×10^6 g/m^3) respectively

c_w and c_m = specific heats of water (4.18 J/g/°C) and matrix (0.84 J/g/°C) respectively

V = volume of aquifer (6×10^{11} m^3)

$\theta_m - \theta_g$ = 10°C drop in temperature applied.

$H_0 = [(0.1 \times 1 \times 10^6 \times 4.18) + (1\text{-}0.1)(2.5 \times 10^6 \times 0.84)] \times 6 \times 10^{11}(10)$

$= 1.38 \times 10^{19}$ J

$\underline{= 1.4 \times 10^{13}\ \text{MJ}}$.

The temperature drop of 10°C is fairly conservative, so there can be a high degree of confidence in the above result.

Conversion from MJ to kWh:

1 kWh = 3.6 MJ, thus 1.4×10^{13} MJ = 3.85×10^{12} kWh

$\underline{= 4 \times 10^{12}\ \text{kWh}}$.

So, the Geothermal Resource of the mined areas of the Midland Valley is estimated to be
1.4×10^{13} MJ or 4×10^{12} kWh.

We consider this to be the total available heat resource (heat in place) in the mined areas of the Midland Valley, but in fact additional heat will flow into this body of rock from the Earth‘s interior, and also solar radiation at shallower levels, replenishing the source to some extent. Only a small proportion of the total heat resource is likely to be recovered/recoverable.

Identified Resource:

If a maximum recovery factor of 0.625 (F = 0.25) is applied this would equate to an Identified Resource of $5{*}10^8$ kWh/km^2.

In this study the accessibility of the resource is calculated using the ―flow rate method" (sections 6.6.2 and 6.7.4) which applies hydrogeological understanding to the problem, so less heed is taken of the Identified Resource calculation.

6.7.3 Geothermal Resource by unit area

It is useful to know, on average, what the Geothermal Resource is per unit area. Dividing the Geothermal Resource for the whole area by the number of square kilometres in the mined area provides us with a value of Geothermal Resource per km^2:

$= 4 \times 10^{12}$ kWh / 4.8×10^3 km^2

$= 8*10^8$ kWh/km^2.

6.7.4 Accessible heat resource from the mined areas of Scotland

The flow rate method has been applied to estimates of thermal resource on regional and national scales. This is done by estimating an available water yield (given as a flow rate) for an area and calculating how much energy can be extracted from that water, or by gathering information about a number of sites, and summing the thermal resource estimates for those sites to produce a regional figure. In mining areas, data usually relate to pumping water to permit mining to proceed and not to the understanding of the hydrogeological regime and water balance. Of necessity, assumptions have to be made and estimates can have large margins of error. These estimates do however identify where more data are required to increase confidence to proceed.

In Section 6.5.3 a yield of 5 to 25 l/s per borehole seems reasonable. Assuming that this yield could be achieved in boreholes spaced on a 500 m grid across the mined area, i.e. 4 boreholes per km^2, we suggest that the groundwater could be exploited at a rate of 20 to 100 l/s/km^2. This rate of pumping would be far in excess of the natural recharge rate and would be unsustainable without re-injection of the water to the aquifer after heat has been extracted.

Example calculation

Using the equation (see section 6.6 for definition of parameters)

$G = Z \,.\, \Delta\Theta \,.\, S_{VCwat}$

where:

$Z = 60$ L/s/km^2 yield

$\Delta\Theta = 10$ ˚C temperature drop

$S_{VCwat} = 4180$ J K^{-1} L^{-1}

$G = 60 \times 10 \times 4180$

$= 2.5 \times 10^6$ W/km^2

= 2508 kW/km^2.

Range of values

The possible range in values of energy that can be extracted per square kilometer is given in Table 10. Taking the middle of the parameter ranges, we can say that some 2.5 MW/km^2 could be obtained on average in the mined areas of Scotland.

Multiplying this value by the number of square kilometres in the mined area (4.8×10^3 km^2) gives a very approximate estimate of the rate at which heat could be accessed of 12 000 MW, or 12 GW.

We consider this to be an estimate of the accessible resource, i.e. how much heat energy could theoretically be extracted from the mined areas of the Midland Valley bearing in mind the hydrogeological constraints (how much water can in practice be abstracted).

Yield (L/s/km^2)	Temperature drop 5°C (kW/km^2)	Temperature drop 10°C (kW/km^2)	Temperature drop 15°C (kW/km^2)
20	420	840	1260
60	1254	2508	3762
100	2090	4180	6270

Table 10 Thermal potential per km^2 based on flow rate method, taking into account possible variability in borehole yields and groundwater temperature .

6.7.5 Proportion of Scotland's heat demand

PB Power (2004) estimated that the total heat demand in Scotland was approximately 55.8 TWh per annum. By 2020, annual demand is expected to be 60.1 TWh (Scottish Government, 2009).

Heat usage is rarely constant; when sizing heat pump systems it is usually assumed that domestic systems run for 1,800 hours per year, and commercial systems for 1,500 hours per year. Dividing the 2020 figure for annual demand by the domestic value of 1,800 hours per year gives a rate of heat use of 0.033 TW, or 33 GW. The commercial value gives a figure of 40 GW.

Comparing this to the estimated rate at which heat could be accessed from mine waters using GSHP, 12 GW (section 6.7.4), we can estimate that the mine waters could theoretically provide the equivalent of approximately one third of Scotland's heat demand. However, the actual contribution is likely to be significantly less for three main reasons:

1. heat cannot be transported efficiently over large distances, so would only be used above or close to suitable mine workings;
2. a proportion of mine workings will not be suited to heat extraction;
3. heat delivered by GSHP is most effectively used in new build properties; existing building stock will likely require extensive upgrading to benefit from mine water heat.

The Scottish Government has set a target of 11% of non-electrical heat demand in Scotland to come from renewable sources by 2020 (Scottish Government, 2011). Based on the calculations set out above, heat from mine waters has the potential to make a significant contribution towards attaining this target,

6.7.6 How many years supply?

If Scotland accessed as much of the heat in the mine waters as possible (2.5 MW/km^2: section 6.7.4), it may last for approximately 37 years. This ignores the reality that additional heat would flow into the mined areas from Earth's interior and solar input. Practicalities also mean that it is unlikely to be possible to access the heat at the maximum possible rate, in which case the supply that is tapped will last longer than the above estimate. Nor does the estimate take into account potential recharge from using the minewaters as a source of cooling during the summer.

6.8 FUTURE POSSIBILITIES

The Coal Authority dataset on the spatial extent of abandoned mines (section 6.5.1), with detail regarding the number and depth of seams worked in different locations, could be used to produce spatially varying estimates of the heat resource in Scotland's mine waters. The data could be used in a GIS to divide Scotland's mined areas into parcels based on categories such as the depth of mining and number of seams mined. Any proposed scheme to utilise heat from mine waters would require a comprehensive geological and hydrogeological desk study and modelling of data prior to any site-specific works. The desk study should make use of the detailed information available from the Coal Authority where possible.

All estimates could be greatly improved if the GSHP industry could provide data about schemes that have already been installed. Access to a mine water GSHP scheme during the drilling stage would enable hydrogeologists to assess the state of the subsurface and do some tests to assess permeability. It would also be valuable to have a research project that monitored the functioning of a Scottish GSHP mine water scheme over a number of years to look at issues such as thermal breakthrough.

Although not considered in this study, mines other than coal mines could also be used for mine water heat recovery. Within the Midland Valley, the greatest potential is likely to be from limestone, ironstone and oil-shale mines (Figure 11). Smaller, more local, mine water resources also exist outside the Midland Valley, for example lead mines in more rural areas such as at Leadhills and Wanlockhead in the Southern Uplands.

6.9 CONCLUSIONS

1. Mine water in abandoned workings in Scotland's Midland Valley might form an important low enthalpy resource for space and domestic hot water heating, and related uses. Our estimates indicate that there is a significant amount of heat (12 GW) in place in the mined areas of the Midland Valley, and that due to the additional permeability provided by mining this heat should be accessible to GSHP schemes. We estimate that mine waters could potentially provide a significant proportion of Scotland's heat demand.

2. However, there are many assumptions and generalisations in this attempt to characterise the heat potential of the Midland Valley and further work is recommended.

6.10 RECOMMENDATIONS

R4 One or more site-specific studies should be conducted utilising existing information (including Coal Authority and BGS data), developing a detailed 3D model of the mine workings, gathering new information on borehole yields and permeability, and assessing the technical feasibility of installing an open loop GSHP system perhaps in combination with other forms of energy. The Glasgow area would be an obvious target given the availability of BGS 3D geological models and other previous studies as well as the expected scale of the ongoing developments and urban regeneration.

R5 The GSHP industry should be encouraged to deposit key data on installed schemes in a national archive, similar to that for borehole data held by BGS to facilitate further modelling and potential exploitation of available thermal resources.

7 Hot sedimentary aquifers

7.1 INTRODUCTION

Hot Sedimentary Aquifer (HSA) settings with the potential to yield commercially viable quantities of warm water require substantial units of permeable sedimentary strata. Most of Scotland is underlain by relatively impermeable crystalline (non-sedimentary) rocks; the Midland Valley is the largest onshore area to be underlain by sedimentary strata. Reviews of the distribution, character and productivity of aquifers in the near-surface zone (to a depth of around 200 metres) in Scotland are presented in MacDonald et al. (2005), Graham et al. (2009), and Ó'Dochartaigh et al. (2011). The properties of aquifers at deeper levels are still largely unknown.

The first, and so far only, successful HSA system developed in the UK is in Southampton (Barker et al., 2000; http://www.southampton.gov.uk/s-environment/energy/Geothermal/). Opened in 1986, the system exploits warm water (<80°C) at a depth of nearly 2 kilometres in sedimentary strata of the Wessex Basin. A combined heat and power (CHP) system delivers sustainable supplies of heat (district heating), chilled water and electricity.

7.2 PREVIOUS INVESTIGATION OF GEOTHERMAL POTENTIAL IN SCOTTISH AQUIFERS

The geothermal potential of sandstone aquifers in the Upper Devonian and Carboniferous strata of the Midland Valley of Scotland was investigated as part of the 'Investigation of the geothermal potential of the UK' project in the 1980s (Browne et al., 1985; Browne et al., 1987). The investigations included: identifying areas where thick, permeable and porous sandstone sequences might occur; considering the depositional environment (desert, river-bed and river delta) of different sandstone units, as these typically produce distinct characteristics that will influence aquifer potential; assessing aquifer properties (permeability, porosity, flow rate etc) from outcrop studies, borehole records and lab testing; and reviewing the evidence from geophysical surveys for deep sedimentary basins.

Key conclusions from these investigations are summarised below.

- The Midland Valley is geologically complex, making it difficult to correlate between boreholes and extrapolate below the ground surface. Interpretation in some areas is complicated further by the influence on groundwater flow of abandoned and active coal mines. The aquifers are typically of variable lithology, intruded by relatively impermeable igneous rocks, fractured, faulted and generally complex.
- The average temperature gradient (based on borehole temperature versus depth [T-z] data) for boreholes in the Midland Valley was reported to be 22.5°C/km[3].

[3] This is significantly lower than the value suggested in this report for onshore boreholes in Scotland (30.5 °C/km; section 4.2), which was interpreted from a dataset dominated by the same boreholes in the Midland Valley. The difference is because the data have been interpreted in different ways. Browne et al. (1987) 'pinned' the top of their interpreted geothermal gradient to a surface temperature of 10 °C (representing the present day surface temperature at Grangemouth); this approach makes the gradient significantly lower than it would be if the top of the gradient is not pinned in this way. The top end of the temperature gradient (or averaged geothermal gradient) reported in section 3.4 of this report is not pinned to surface temperature.

- In general, water moving through aquifers at deeper levels is likely to be of relatively small volume and confined to discrete zones of flow.
- The Knox Pulpit Sandstone Formation is the main HSA prospect in the Midland Valley. This unit, which is a component of the Upper Devonian Stratheden Group, crops out in northern Fife and may persist beneath other parts of Fife, Clackmannanshire and the Glasgow area at depths of up to 4 kilometres. The formation, which is composed of weakly cemented, wind-deposited (as opposed to water-deposited) sandstone, is around 170 metres thick but the aquifer of which it is part can be considered to include some of the overlying and underlying strata.
- A borehole drilled in Glenrothes as part of the same project (the Glenrothes Heat Flow Borehole) showed that the favourable porosity and permeability characteristics that occur at outcrop in the Knox Pulpit Sandstone Formation are reduced at depth. However, the average horizontal permeability and transmissivity at a depth of 500 metres remained relatively high.
- Most of the sandstone aquifers in Carboniferous strata are likely to be of little geothermal interest due to a combination of their physical properties, relatively modest thicknesses and limited regional distribution. However, the most deeply buried sandstone units in some Carboniferous sequences, notably the Passage Formation in Clackmannanshire, Fife and the Lothians, may have geothermal potential.

7.3 HSA POTENTIAL BASED ON BEDROCK AQUIFER PRODUCTIVITY

This assessment of HSA potential in Scotland is based on published studies of bedrock aquifer productivity. Figure 24 shows how the ‗productivity‘ of bedrock units within the near-surface zone (less than c. 200 metres below ground) varies across Scotland (‗productivity‘ is a qualitative measure of aquifer quality, and is based on several quantitative hydrogeological parameters). The most productive (‗very high productivity‘) rock units are confined to a number of relatively small occurrences of Permo-Triassic rocks in south-west Scotland and a single strip of Devonian sandstone in Fife. Large areas of somewhat less productive (‗high‘ and ‗moderate‘ productivity) sedimentary rocks of Devonian and Carboniferous age crop out across much of the Midland Valley, in the Scottish Borders area, and on the margins of the Moray Firth to the north and east of Inverness. Virtually all of the Highlands, islands and Southern Uplands are characterised by poorly productive rocks (‗low‘ and ‗very low‘ productivity).

The level of aquifer ‗productivity‘ that would be required to support a commercially viable HSA scheme is likely to vary according to a range of factors, including the depth of the resource and water temperature. For the purposes of this assessment, it is assumed that only units classified as having ‗very high‘ or ‗high‘ productivity on Figure 24 have HSA potential (see Ó‘Dochartaigh et al., 2011 for definitions). A brief description of these units is presented below (see Figure 25 for locations of the best HSA prospects described below).

An important point to consider when assessing settings with HSA potential is that the ‗productivity‘ of a rock unit can change with depth. Sedimentary rocks with a significant proportion of intergranular (or matrix) pore space at the time they were deposited (principally sandstones and conglomerates) may be particularly prone to depth-related changes in permeability. With increasing depth, the weight of overlying rock can reduce intergranular porosity and cause near-horizontal fractures to close. The same downward force can cause near-vertical fractures to form or widen. Water chemistry (acidity, oxidising potential, salinity etc) and temperature also change with depth; these changes can cause new minerals to form in pore spaces (thereby reducing permeability) and they can cause existing minerals to dissolve (thereby increasing permeability). The net effect of all these changes on aquifer productivity will vary spatially (and over time) within the rock mass, and cannot be predicted with certainty from surface or near-surface observations alone. Testing in deep boreholes will be required to gauge the actual permeability and overall productivity at depth in any setting with HSA potential.

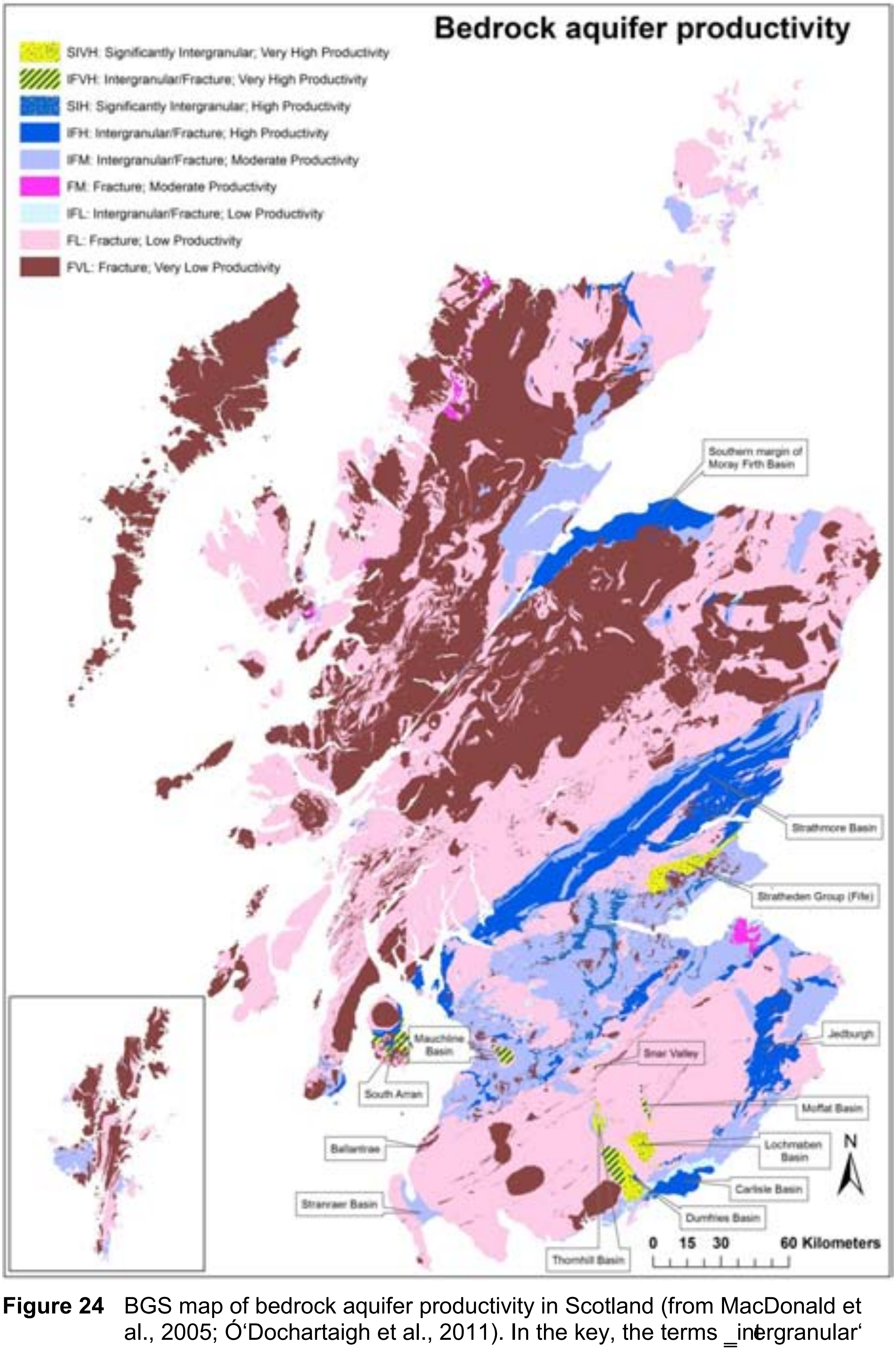


Figure 24 BGS map of bedrock aquifer productivity in Scotland (from MacDonald et al., 2005; Ó'Dochartaigh et al., 2011). In the key, the terms ‗intergranular' and ‗fracture' refer to the dominant type of pore space in the bedrock unit. See text sections 3.1 and 7.3 for details.

7.3.1 „Very high" and „high" productivity aquifers

7.3.1.1 PERMIAN AND TRIASSIC ROCKS

Several relatively small areas of Permo-Triassic rocks in south-west Scotland have been identified as having ‗very high productivity'. These rock units are geologically isolated (i.e. they sit apart from other, similar rock units of the same age) and consist mainly of red sandstone and conglomerate, with occasional thin flows of basaltic lava. Their locations are shown on Figure 24 and summarised here:

- In the Mauchline Basin of Ayrshire, a thickness of around 450 metres of Permian sandstone overlies up to 300 metres of interbedded igneous and sedimentary rocks.
- The southern part of Arran is dominated by Permian and Triassic mudstone, sandstone and conglomerate to a depth of possibly several hundred metres.
- The Stranraer Basin is asymmetric and bounded on its east side by a fault. Geophysical evidence shows that it contains a thickness of up to 1,200 metres of Permian and possibly Carboniferous strata near its eastern margin.
- The Ballantrae Basin lies mostly offshore, but between Ballantrae and Bennane Lea in Ayrshire a thickness of some 750 metres of lower Permian strata form coastal exposures at the basin margin. The strata contain at least one layer-parallel unit of doleritic rock around 1 metre thick.
- Geophysical modelling indicates the deepest part of the Thornhill Basin holds a maximum combined thickness of around 400 metres of Permian and underlying Carboniferous strata, in which sandstone and conglomerate are interdigitated locally with thin basalt lava flows.
- The Dumfries Basin is a broadly symmetrical structure containing a sequence of conglomerate and red sandstone that is estimated from geophysical modelling to attain a maximum thickness of approximately 1,500 metres.
- From geophysical evidence, the Lochmaben Basin contains a maximum thickness of around 1,300 metres of sandstone, conglomerate and rare basalt.
- The Moffat Basin is a narrow, elongate trough containing a thickness of around 200 metres of conglomerate and red sandstone.
- A sequence up to 700 metres thick of Permian conglomerate occupies what appears to be a palaeogeographical depression (as opposed to a fault-bounded structure) in the Snar Valley.
- Permian to Triassic strata that crop out around Annan and Gretna form the marginal sequence to the large Carlisle Basin, most of which lies to the south of the border with England. The basin extends offshore under the innermost part of the Solway Firth.

The largest and deepest of these basins may have Hot Sedimentary Aquifer potential (Figure 25). None of the heat flow data or borehole temperature data described in section 4 was derived from boreholes through these rocks, so there are no directly measured geothermal data. Applying the ‗regional geothermal gradient' inferred from Figure 9 suggests temperatures of approximately 40–50°C should be encountered in the deepest parts of the Stranraer, Dumfries and Lochmaben basins. Layers of generally basaltic (low thermal conductivity) igneous rock, which occur locally within the mainly sedimentary strata, may act to trap heat and water locally.

7.3.1.2 DEVONIAN ROCKS

A strip of strata assigned to the Stratheden Group in the northern part of Fife (the Knox Pulpit Sandstone Formation referred to in section 7.2) is the only occurrence at outcrop in Scotland of Devonian rocks with ‗very high productivity' (Figure 24). The Stratheden

Group consists mainly of red-brown sandstones with subordinate conglomerate and mudstone. In onshore parts of Fife the unit may attain a thickness of around 500 metres, but it extends offshore into the Firth of Tay and is considerably thicker there. In Fife, the Stratheden Group is underlain mainly by Devonian volcanic rocks.

Applying the ‗regional geothermal gradient‘ to this setting suggests a temperature of approximately 22°C would be encountered towards the base (c. 500 metres deep) of the Stratheden Group beneath its outcrop in Fife. Stratheden Group strata are overlain locally by extensive layers of doleritic (silica-poor) igneous rocks up to several hundred metres thick forming the Lomond Hills, and these may to some degree trap heat and water in the Stratheden Group rocks beneath them.

Units of Devonian sandstone with ‗high productivity‘ crop out within substantial areas of ground bordering the southern edge of the Moray Firth, in the northern half of the Midland Valley, and around Jedburgh in the Scottish Borders (Figure 24).

There are no deep boreholes through the Devonian rocks adjacent to the southern edge of the Moray Firth, so there are no directly measured temperature data and the thickness of sedimentary rocks sitting on crystalline basement rocks has not been proved. The sequence in general thickens towards the coast, and the total thickness of Devonian strata is likely to reach at least 3,000 metres in places close to the coast. Applying the ‗regional geothermal gradient‘ to this setting suggests a temperature of 107 ±23°C would be encountered towards the inferred base of the Devonian strata (at a depth of ~3 km) close to the coast.

The northern part of the Midland Valley is underlain mainly by Devonian strata, much of which has ‗high productivity‘. The strata originally filled the Strathmore Basin which has subsequently been deformed into a broad fold, the Strathmore Syncline. The strata consist dominantly of sandstone, with subordinate but locally substantial units of conglomerate and mudstone, and in places thin to thick, silica-poor to silica-rich lavas. The thickness of the sequence probably varies significantly across the outcrop, and in places may exceed five kilometres. If the ‗regional geothermal gradient‘ applies to this setting, there is clearly considerable potential for HSA resources (temperatures may reach or exceed 100°C at a depth of 3 km and 150°C at 5 km), but more detailed investigation than has been possible here is required to identify specific targets with HSA potential beneath this large area.

A large area of Devonian strata assigned to the Stratheden Group crops out around Gordon and Jedburgh in the Scottish Borders region. The unit is estimated to be up to 200 metres thick and to consist of sandstone and siltstone above a basal layer of conglomerate. The temperature at the base of the unit is probably no higher than 15°C, and it is therefore unlikely to have significant HSA potential.

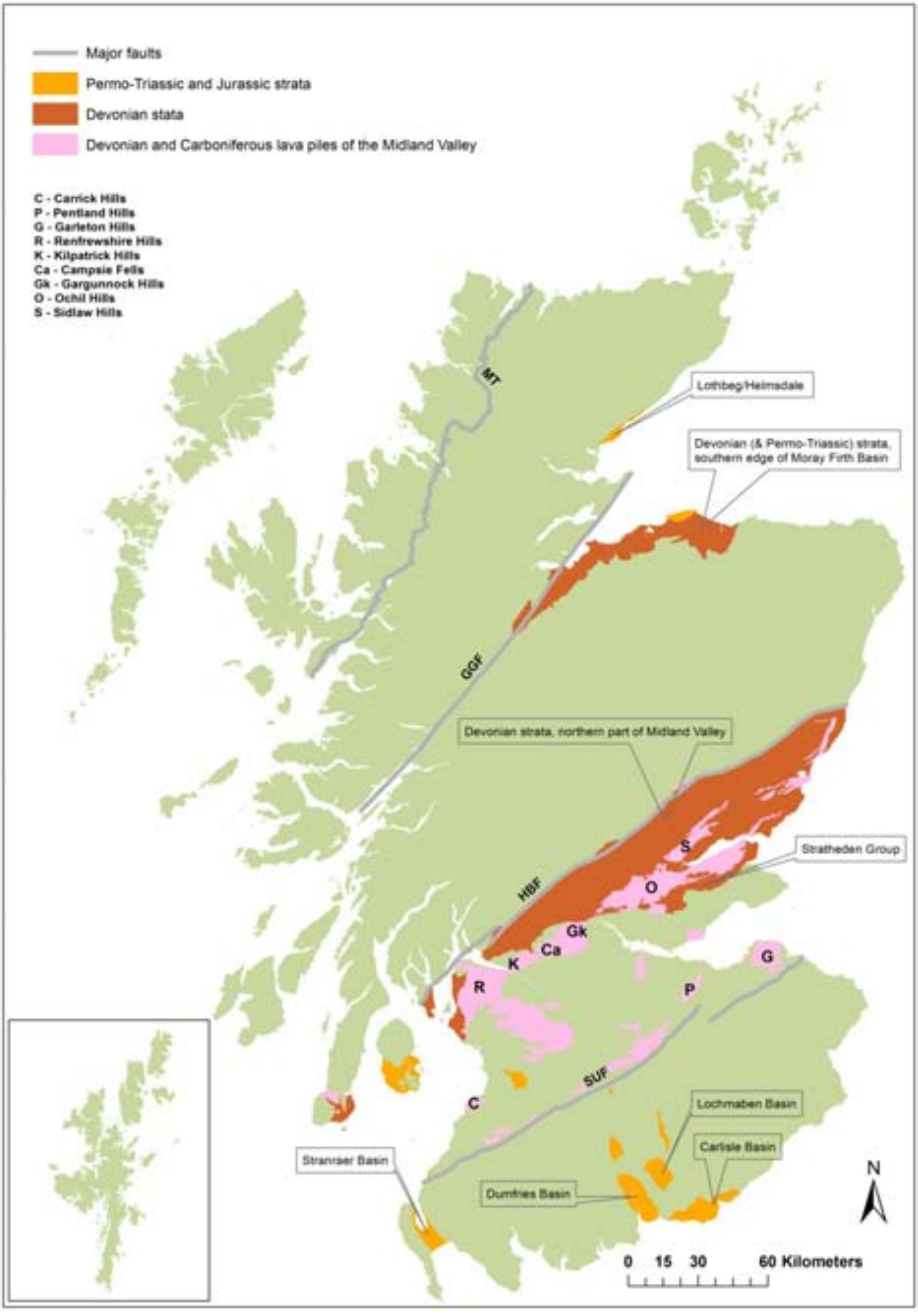


Figure 25 Rock units which on geological grounds appear to have good HSA potential. The Devonian and Carboniferous lavas of the Midland Valley do not have HSA potential, but locally they may overlie sedimentary strata that do. See text for details. See Figure 3 for abbreviations.

7.4 ONSHORE MARGINS OF OFFSHORE BASINS

The average temperature gradient in two of the boreholes represented on Figure 6 and in Table 4 is notably high compared to others in the same region: a temperature of 40.6ºC at a depth of 736 metres in the Lothbeg borehole (on the coast just south of Helmsdale in Caithness; see Figure 4) equates to an average temperature gradient of 42.9ºC/km; and a temperature of 61.2ºC at a depth of 1,365 metres in the Archerbeck borehole (around 20 km east-north-east of the Solway Firth; see Figure 4) equates to an average temperature gradient of 37.9ºC. Both values lie above (on the ‗hot‘ side of) the trend defined by all of the data in Figure 6 and Figure 9, suggesting the boreholes have penetrated local thermal anomalies. The Lothbeg borehole was drilled by an oil company in sedimentary rocks of Jurassic age in the coastal zone south of the Helmsdale granite intrusion, while the Archerbeck borehole intersects a thick and lithologically variable sequence of Carboniferous rocks a few miles inland of the Solway Firth. The Helmsdale granite has HHP character, and the high average temperature gradient at Lothbeg might therefore reflect elevated heat flow above buried HHP granite; however, the evidence from geophysical survey data does not indicate the presence of buried granite at depth. An alternative explanation may lie in the proximity of both boreholes to deep offshore sedimentary basins (the Inner Moray Firth Basin and the Solway Basin, respectively). Hot water from deeper parts of the offshore basins may have migrated to shallower levels in the onshore margins of the basins. The hydrogeological ‗driver‘ for migration onshore of offshore water is not clear, but the greater density of saline (offshore) water compared to fresh (onshore) water may play a role. A further possible explanation for high temperature at the bottom of the Lothbeg borehole may lie in the proximity of the Great Glen Fault (Figure 4). The outcrop of this major geological discontinuity lies a short distance off the east coast of Caithness, between the main part of the Moray Firth Basin and the Lothbeg borehole, and the fault may play an important role in controlling the movement of water around the basin margin. The high temperature at the bottom of the Lothbeg borehole may indicate that the Great Glen Fault in this area acts as a conduit for hot water moving upwards from depth.

The possibility that thermal anomalies exist in some onshore margins of large offshore basins needs more investigation. However, if it proves to be the case then other parts of the Scottish coastline may harbour potential HSA resources. For example, the Stranraer, Dumfries and Carlisle basins mentioned in section 7.3.1.1 are all connected geologically (and presumably hydraulically) to much larger, deeper basins offshore (i.e. they represent the onshore margins of deeper offshore basins), as do the outcrops of Permian rock at Ballantrae (Ayrshire) and in south Arran (Figure 25).

It may prove possible in some places to access HSA settings at depth in offshore (near-shore) sedimentary basins by drilling inclined boreholes from onshore coastal locations, though this is likely to be expensive and may not be economically justifiable.

Extracting geothermal energy from salty water (from offshore settings) would involve challenges (e.g. metal corrosion and potential contamination of fresh water aquifers) that are not presented by fresh water, but these can be overcome.

7.5 HSA PROSPECTS BENEATH LOW THERMAL CONDUCTIVITY ROCKS

Thick sequences of basaltic and andesitic igneous rocks (lavas and pyroclastic deposits) overlie sedimentary rocks with HSA potential in several parts of the Midland Valley. These igneous rocks typically have low productivity, and as such are very unlikely to be HSA prospects themselves. However, they also have relatively low thermal conductivity, and they may therefore act to trap both heat and water in sedimentary aquifers beneath them. Thick sequences of Devonian basaltic and andesitic rocks underlie the Ochil Hills and Sidlaw Hills in the north-east part of the Midland Valley, and the Carrick Hills and Pentland Hills (amongst other areas) in the southern part (Figure 25). Thick sequences of Carboniferous basaltic rocks underlie the Renfrewshire, Kilpatrick, Campsie and Gargunnock hills in the west part of the Midland Valley, and the Garleton Hills in the east. In other parts of the Midland Valley, the same sequences of igneous rocks will be buried beneath younger sedimentary rocks; in these areas, sedimentary strata with HSA potential may be encountered at relatively deep levels beneath the igneous strata.

It is emphasised that there is at present no direct evidence to support the existence of thermal anomalies beneath igneous rocks in any of these areas. New heat flow measurements may reveal the presence of local thermal anomalies, and new boreholes could test whether temperature and/or aquifer productivity increases beneath a thick pile of igneous rocks. The igneous strata in the Midland Valley typically form substantial upland massifs, and it may be possible to access the sedimentary rocks beneath some massifs by drilling inclined boreholes from low ground beside the massifs rather than drilling vertically through them.

7.6 CONCLUSIONS

1. Based on geological factors only, the Devonian strata to the east of Inverness (forming the southern onshore margin of the Moray Firth Basin) and in the northern part of the Midland Valley (notably the Knox Pulpit Sandstone Formation), and Permo-Triassic strata filling the Dumfries, Lochmaben, Stranraer and Carlisle basins in south-west Scotland, have the greatest HSA potential in Scotland. However, the permeability (and hence productivity) of a rock unit can change with depth, and the nature and effect of such change cannot be predicted with certainty from surface or near-surface observations alone.

2. Relatively high temperatures reported from two boreholes drilled into onshore outcrops of mainly offshore basins (at Lothbeg near Helmsdale and Archerbeck near Dumfries) suggest that hot water sourced from deeper levels offshore may have moved to shallower levels in onshore parts of the basin margins; if so, then these and other parts of the Scottish coastline representing the onshore margins of offshore basins may harbour potential HSA resources. It may prove possible in some places to access HSA settings at depth in offshore (near-shore) sedimentary basins by drilling inclined boreholes from onshore coastal locations, though this is likely to be expensive and may not be economically justifiable.

3. Virtually all of the Highlands, islands and Southern Uplands regions are characterised by rocks with ‗low‘ or ‗very low‘ aquifer productivity, and these rock units are likely to have little or no HSA potential.

7.7 RECOMMENDATIONS

For Hot Sedimentary Aquifer (HSA) settings we recommend:

R6 More detailed investigation of parts of the Midland Valley (possibly including the Strathmore Syncline and buried parts of the Knox Pulpit Sandstone Formation) to identify specific targets with HSA potential.

R7 Further investigation of the possible thermal anomalies in some onshore margins of large offshore basins such as the Moray and Solway firths and the Firth of Clyde.

R8 Testing in deep boreholes to gauge the actual permeability and overall productivity at depth in settings with HSA potential.

8 Hot Dry Rocks (Enhanced Geothermal Systems)

8.1 INTRODUCTION

‘Hot dry rock’ (HDR) resources typically will be deeper and hotter than HSA resources. Consequently, they have the potential to yield much more energy but they will present a much greater technical challenge. Unlike HSA resources, heat is extracted from ‘dry’ crystalline rocks by fracturing them, injecting cool water into the hot fractured rock, and extracting the resulting hot water. This requires the development of an Enhanced (or Engineered) Geothermal System (EGS). A ‘loop’ consisting of boreholes at either end of a network of connected, open fractures must be developed in the hot rock, through which cold water is introduced and hot water is removed. HDR resources yield hot (100–200°C) water (or steam), and the thermal energy stored therein is converted into electricity at the surface. Where the resource already contains hot water in naturally occurring fractures, the term ‘Hot Wet Rock’ (HWR) resource is used.

HDR projects are currently being developed in several parts of the world, including Australia, France, and the USA. Some of these have the potential to yield substantial amounts of energy but as yet none is being operated on a sustainable, commercial basis. Two projects to exploit HDR prospects are currently being developed in the UK, both in the granite intrusions of Cornwall: the United Downs Project (http://www.geothermalengineering.co.uk/page/projects-and-developments.html) and the Eden Deep Geothermal Energy Project (http://www.edenproject.com/support-us/future-plans/eden-deep-geothermal-energy).

The considerable technical challenges and associated costs of developing an HDR resource via EGS means they are likely to be considered only if the resource is big enough to generate large quantities of electricity for a number of decades. It has generally been considered that a heat reservoir temperature of at least 150°C will be required to support a commercially viable HDR project. However, the actual temperature that will be required in a future EGS project at a particular locality depends on a range of factors, including the technology available to convert heat to electricity (which is improving all the time), the size and sustainability of the heat reservoir, and the cost of accessing it (which depends, amongst other things, on its depth and the technology used for drilling and hydraulic fracturing). Additionally, the rising cost of other energy sources and the growing environmental need to develop sources of clean, renewable energy, have the effect of reducing the minimum temperature at which an HDR prospect can be considered commercially viable. In recent years the development of binary cycle power plants, in which electricity can be generated using water that is cooler than 100ºC, has greatly improved the potential for recovering geothermal energy from HDR prospects that previously would have been considered marginal or not viable.

The ‘regional geothermal gradient’ for Scotland described in section 4.2, suggests a temperature of 150°C would be reached at a depth of approximately 4,000 metres, which is within the widely quoted practical lower limit for exploiting HDR resources (5,000 metres). If the more conservative geothermal gradient suggested by borehole temperature data from onshore boreholes is used (30.5°C/km) then 150°C should be encountered at approximately 4,900 metres, still within the ‘accessible zone’. However, the HDR concept is most suited to crystalline rocks, and only 21 of the 133 temperature data that define the trend displayed in Figure 9 were measured in crystalline rocks (15 in offshore boreholes and 6 in onshore boreholes). None of the 21 data lies off the trend, so there is at present no direct evidence from borehole temperature data that the regional geothermal gradient in crystalline rocks is different to that in sedimentary rocks.

Nevertheless, the lack of temperature data for crystalline rocks in deep (> 2 km) onshore boreholes means that caution should be exercised in applying the regional temperature gradient of Figure 9 to potential HDR settings.

Some parts of the crust contain thermal anomalies, wherein the size of the local heat resource exceeds that which is produced by simple ‘background’ heat flow. Finding thermal anomalies at accessible depths should increase the chance of developing viable EGS schemes, because the average geothermal gradient in the crust overlying them is higher than the ‘background’ gradient. This section therefore focuses on whether and where such anomalies might exist.

In Scotland, three situations can be envisaged in which a ‘hot’ thermal anomaly might be produced in ‘dry’ crystalline rocks:

- (i) where the background heat flow is augmented by additional heat generated in situ;
- (ii) where the upward flow of heat is impeded, such that some of it becomes trapped.
- (iii) a combination of (i) and (ii).

Intrusions of High Heat Production (HHP) granite are likely to be the only source of significant additional heat generated in situ within the crust beneath Scotland. For the purposes of this assessment the threshold Heat Production (HP) value above which rocks are considered to have HHP character is 4.0 $\mu W\ m^{-3}$ (section 2.1.2). Rock units with low thermal conductivity provide perhaps the likeliest situation in which the upward flow of heat might be impeded. The potential for both situations to exist in Scotland is discussed below.

8.2 HIGH HEAT PRODUCTION (HHP) GRANITE

8.2.1 The granite intrusions of Scotland

Distribution, origin and HP values

Onshore Scotland has more than 200 intrusions of granite (and similar rocks) at surface which have an area at outcrop of more than 1 km^2. The largest (the Rannoch Moor intrusion) crops out over an area of c. 380 km^2. The intrusions crop out in many parts of the country; however, the greatest concentration (including most of the largest intrusions) is in the block of crystalline rocks bounded by the Highland Boundary Fault and the Great Glen Fault (Figure 3 and Figure 26).

These intrusions have commonly been referred to individually and collectively as ‘granites’. However, many contain, or consist of, rock types other than granite sensu stricto[4] (notably granodiorite and diorite, which are related to granite), and some contain no granite (sensu stricto) at all (Table 11). The lithological distinction is important, because the chemical elements K, U and Th (which produce heat by radioactive decay) generally only reach concentrations that might have geothermal significance in granite sensu stricto; concentrations of these elements are typically too low in petrologically similar but less geochemically evolved rock types like granodiorite and diorite.

The granite intrusions of Scotland formed in association with several geological events.

[4] Granite sensu stricto is a single rock type. The term ‘granite’ is also commonly used sensu lato, to encompass other similar rock types, including granodiorite and tonalite. Individual types of igneous rock, including granite, can be identified in two ways: by the relative proportions of key minerals as they appear in microscope analysis of solid rock; and by the proportions of key chemical elements as they appear in chemical analysis of finely crushed rock.

A small proportion (less than 10) formed in association with a period of crustal stretching that preceded and accompanied the opening of a major ocean (the Iapetus Ocean), around 600 million years ago. These intrusions are granite sensu stricto, they crop out in the Grampian Highlands and Northern Highlands, and they are typically small (with one exception, the Carn Chuinneag intrusion in Easter Ross). There are no published HP data for any of these intrusions, and no published geochemical analyses that include U and Th. However, the geochemical data that have been published suggest the intrusions are not as compositionally evolved as HHP granite, and therefore are unlikely to have HHP character.

By far the largest proportion of Scotland‘s granitic intrusions formed in association with the Caledonian Orogeny, which represents geological events associated with closure of the Iapetus Ocean between 500 and 400 million years ago. Broadly speaking, intrusions of granite and granite-like rocks formed at three different stages of the Caledonian Orogeny, each one associated with a major crustal collision event (Table 11):

- the Grampian Event (c. 490–460 million years ago) produced several large bodies of granite and granodiorite in the region south of Inverness and near Aberdeen. All these intrusions have low HP values, in the range 0.6–2.2 μW m^{-3} (data from six intrusions).
- The Scandian Event (c. 435–420 million years ago) produced numerous intrusions of granite, granodiorite and diorite that occur in greatest concentration in the Grampian Highlands region. HP values range from 2.2–7.3 μW m^{-3} (data from sixteen intrusions) in those intrusions that consist exclusively, or very largely, of granite sensu stricto. In eight of these (the Helmsdale, Fearn, Abriachan, Bennachie, Mt Battock, Ballater, Cairngorm and Monadhliath intrusions), the mean values of HP data match or exceed the threshold for HHP character used in this assessment (4 μW m^{-3}); these intrusions can therefore be designated as having HHP character. Parts of four other intrusions (the Strontian, Ballachulish, Etive and Lochnagar intrusions) also exceed the threshold, though the mean value does not.
- Two large intrusions (Fleet and Criffel) were emplaced in what is now southern Scotland, at the end of the Caledonian Orogeny (c. 410–390 million years ago). The mean HP values are 3 μW m^{-3} and 2.2 μW m^{-3} respectively. However, both intrusions are compositionally zoned, and the central part of the Fleet intrusion may approach the HHP threshold.

Several intrusions c. 350 million years old crop out on Shetland. Each typically contains a diverse range of rock types, from ultramafic (very silica-poor) rock to granite, and their origin is not well understood. There are no published HP data for these intrusions, and no published geochemical analyses that include U and Th. However, the geochemical data that have been published suggest the intrusions are not as compositionally evolved as HHP granite, and therefore are unlikely to have HHP character.

A number of granitic intrusions formed in Scotland around 60 million years ago as a result of igneous activity that was a precursor to, and accompanied, the opening of the North Atlantic

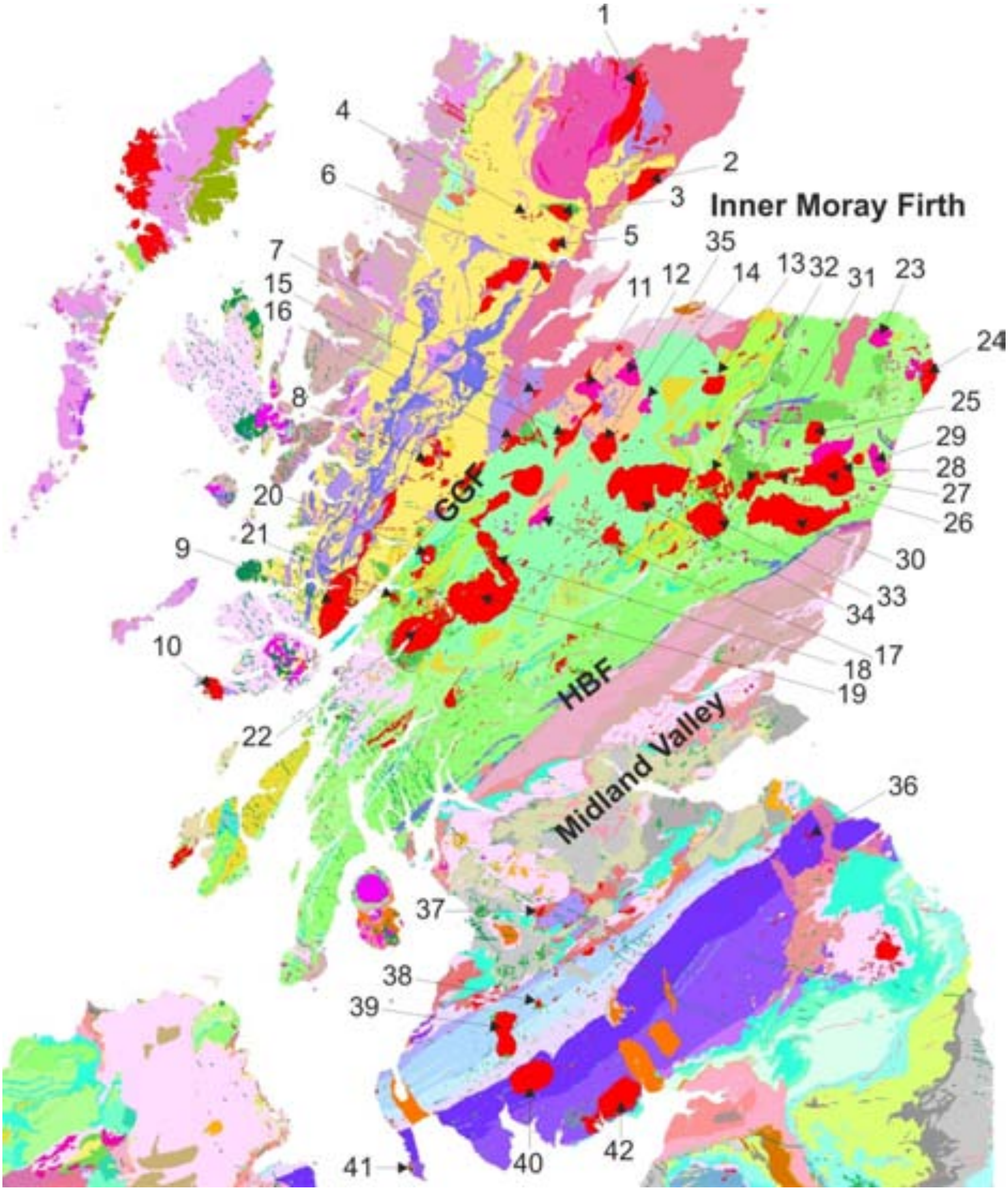


Figure 26 Bedrock geology map of Scotland showing the location of granite intrusions referred to in Table 11 and elsewhere in this report. Map based on BGS Bedrock Geology UK North 1:625 000 map.

Numbers refer to Caledonian intrusions of granitic-rock: 1 Strath Halladale; 2 **Helmsdale**; 3 Lairg-Rogart; 4 Grudie; 5 Migdale; 6 **Fearn**; 7 **Abriachan**; 8 Cluanie; 9 Strontian; 10 Ross of Mull; 11 Moy; 12 Ardclach; 13 Ben Rinnes; 14 Grantown; 15 Findhorn; 16 Foyers; 17 Strathspey; 18 Strath Ossian; 19 Rannoch Moor; 20 Ben Nevis; 21 Ballachulish; 22 Etive; 23 Strichen; 24 Peterhead; 25 **Bennachie**; 26 Coull (Cromar); 27 Hill of Fare; 28 Skene (Crathes); 29 Aberdeen; 30 **Mt Battock**; 31 **Ballater**; 32 Glen Gairn; 33 Lochnagar; 34 **Cairngorm**; 35 **Monadhliath**; 36 Priestlaw; 37 Distinkhorn; 38 Carsphairn; 39 Loch Doon; 40 Fleet; 41 Portencorkrie; 42 Criffell.HBF = Highland Boundary Fault; GGF = Great Glen Fault. High Heat Production intrusions in bold.

Pale pink and dark pink polygons flanking the Inner Moray Firth are Old Red Sandstone sedimentary rocks representing onshore remnants of materials deposited in the former Orcadian Basin. The Orcadian Basin extended across what is now the Inner Moray Firth, the Orkney Islands and Shetland.

Intrusion (a)	**Event** (b)	**HP** (c)	**n** (d)	**Rock type** (e)	**Area** (f)
Strath Halladale	S	(1.4)	(22)	qm, **gd**, g	250
Helmsdale	S	**4.1**	97	**g**	98
Lairg-Rogart	S	1.4	17	qmd, **gd**, g	70
Grudie	S	3.8*	3	**g**	6
Migdale	S	2.4	9	**g**	20
Fearn	S	**5.1***	4	**g**	33
Abriachan	S	**4.0***	2	**g**	4
Cluanie	S	1.1	10	**gd**	18
Strontian †	S	1.9	37	**gd**	200
Ross of Mull	S	1.5*	4	**g**, gd	140
Moy	G	2.1*	6	**g**, gd	56
Ardclach	G	1.4*	4	**g**, gd	63
Ben Rinnes	S	3.2*	6	**g**	55
Grantown	G	1.3	6	**g**	25
Findhorn	S	1.4	10	**gd**, qd, d	90
Foyers	S	1.1	72	d, qmd, qd, gd, g	80
Strathspey	G	0.6	5	**g**	36
Strath Ossian	S	2.2	6	qd, **gd**, g	112
Rannoch Moor	S	1.7	34	md, qmd, gd, g	380
Ben Nevis	S	1.8	18	qd, t, gd, g	40
Ballachulish †	S	3.2	17	d, md, g	30
Etive †	S	1.9	236	qd, md, g	300
Strichen	G	2.2*	2	**g**	50
Peterhead	S	2.2	18	**g**	136
Bennachie	S	**5.7** (**7.0**)	32 (8)	**g**	55
Coull (Cromar)	S	2.6*	2	**g**	17
Hill of Fare	S	3.9*	2	**g**	37
Skene (Crathes#)	S	1.6	17	t, **gd**, g	240
Aberdeen	G	2.2	3	**g**	90
Mt Battock	S	**5.0** (**4.8**)	48 (6)	**g**	370
Ballater	S	**5.7** (**6.8**)	34 (9)	**g**	48
Glen Gairn	S	2.8*	8	**g**	62
Lochnagar †	S	2.7*	14	**g**	150
Cairngorm	S	**5.0** (**7.3**)	233 (9)	**g**	365
Monadhliath	S	**5.7***	6	**g**	113
Priestlaw	S	1.4*	2	d, gd, g	8
Distinkhorn	S	2.0*	4	d, gd	8
Carsphairn	S	2.2*	17	d, gd, g	13
Loch Doon	S	2.5	164	d, **gd**, g	200
Fleet		3.0	146	**g**	150
Portencorkrie	S	2.1	4	d, gd, g	5
Criffell		2.2	18	gd, g	200

Table 11 Heat production values of the largest intrusions that formed in Scotland during the Caledonian Orogeny. Grey shading highlights those that consist largely or entirely of granite sensu stricto at outcrop.

(a) † Lee et al. (1984) reported that parts of these zoned intrusions have heat production values exceeding 4 μW/m^{-3}. # the ‗Skene‘ intrusion is now divided into the Crathes, Tillyfourie and Kemnay intrusions. (b) G = Grampian, S = Scandian. (c) Heat production data from Lee et al. (1984), Tables 5.1 and 8.1. All values are the mean of surface heat production data (μW/m^{-3}), except values in brackets which are the ‗preferred‘ values of Wheildon et al. (1984) and Lee et al. (1984) measured in borehole samples with corrections for topography. Values in bold text exceed the threshold for HHP plutons, as defined here (4 μW/m^{-3}). * The distribution of samples and variability of data was considered by Lee et al. (1984) to be inadequate for deriving confidently a satisfactory value. (d) Number of samples used to calculate the mean. (e) Dominant rock type in bold: d = diorite; md = monzodiorite; qd = quartz-diorite; qmd = quartz-monzodiorite; qm = quartz-monzonite; t = tonalite; gd = granodiorite; g = granite. (f) Approximate area at outcrop, in km^2.

Ocean. They crop out exclusively off the west coast, and are exposed on the islands of Skye, Rum, Mull, Arran and Ailsa Craig. A significant number of intrusions of this age also crop out on the sea floor off the west coast of Scotland. They all consist of, or contain, granite sensu stricto; however, there are no published HP data and no published geochemical analyses that include U and Th. The geochemical data that have been published suggest the intrusions are unlikely to have HHP character.

In summary, the existing dataset of HP values (which is far from complete) suggests that HHP character is a feature mainly of the granite intrusions associated with the late Caledonian Scandian Event in Scotland. Granite with HHP character is known to occur in twelve intrusions that formed during this event: in eight of these the mean values of surface-derived HP data exceed the threshold for HHP character used in this assessment (4 μW m^{-3}); the remaining four are zoned intrusions in which some part of the intrusion exceeds the threshold.

The distribution of HHP rock in HHP granite intrusions

A typical granite intrusion is an enormous three-dimensional rock mass. The HP capacity of rocks is typically quantified by analysing rock samples collected at outcrop or from shallow boreholes. Such samples only represent a two-dimensional ‗slice‘ through the rock in the intrusion, and it is generally not possible to say how representative the results are of the intrusion as a whole. Single intrusions commonly consist of two or more chemically distinct batches of magma and some of these may not be exposed at outcrop. Furthermore, magma usually changes its chemical composition as it moves through the crust. The net result is that the composition of rocks can change from place to place, horizontally and vertically, within a single intrusion. In intrusions where HHP granite is exposed at outcrop, it is generally not possible (in the absence of a deep borehole) to predict with certainty to what depth and within what volume of rock the HHP character persists. The presence of HHP rock in some part of the outcrop of an intrusion does not mean that the intrusion as a whole has HHP character. Conversely, the absence of HHP rock in the outcrop of a granite intrusion does not mean that there is none at deeper levels (though it is probably unlikely in most cases). Detailed geochemical mapping of the outcrop, or heat flow measurements in shallow boreholes across the outcrop, might help to determine whether HHP rocks are likely to exist at depth, but ultimately a deep borehole will be required to prove it.

The top (shallowest) part of an intrusion is called the roof zone, and the most geochemically evolved rocks in a granite intrusion are commonly found in, or towards, the roof zone. The highest concentrations of the radiothermal elements K, U and Th are commonly found in the most geochemically evolved rocks, so in some intrusions the rocks with the highest HP values are in the roof zone. The thickness of roof zones is in general difficult to gauge; in intrusions where the roof zone is exposed at outcrop, the top of the roof zone has generally been eroded away (Figure 27) and the base is commonly gradational rather than abrupt. The thickness of roof zones is likely to vary considerably between intrusions, and probably also across individual intrusions. Based on limited field and borehole information for large granite intrusions in Scotland, the roof zone in some cases may attain a thickness of 1 to 2 km.

Large intrusions can span a depth range of more than 10 kilometres at the time they are emplaced in the crust. All the intrusions that are currently exposed at outcrop in Scotland have been eroded to some degree: in some, the current land surface intersects the roof zone while in others it is below the roof zone (i.e. the roof zone has been removed by erosion). Intrusions that are currently not exposed (i.e. are concealed beneath other rocks) may never have been exposed, in which case the roof zone will still be intact at the top of the intrusion (Figure 27). Alternatively, they may have been exposed and partially eroded in the past, then buried beneath sedimentary rocks; in such cases the roof zone may have been removed by erosion.

It is generally difficult to determine from outcrop information alone what part of an intrusion the currently exposed level represents. However, some of the geochemical and physical features of an exposed granite intrusion may indicate that the exposed level is in, or near to, the roof zone. These include: the presence within the granite of blocks of the rock that was originally above the intrusion and were detached and incorporated by the invading granite magma; features that point to a rapid increase in magma vapour content, such as small cavities in the rock, veins of quartz or coarse granitic rock, and associated chemical alteration; and textural evidence for de-gassing or venting of the magma chamber.

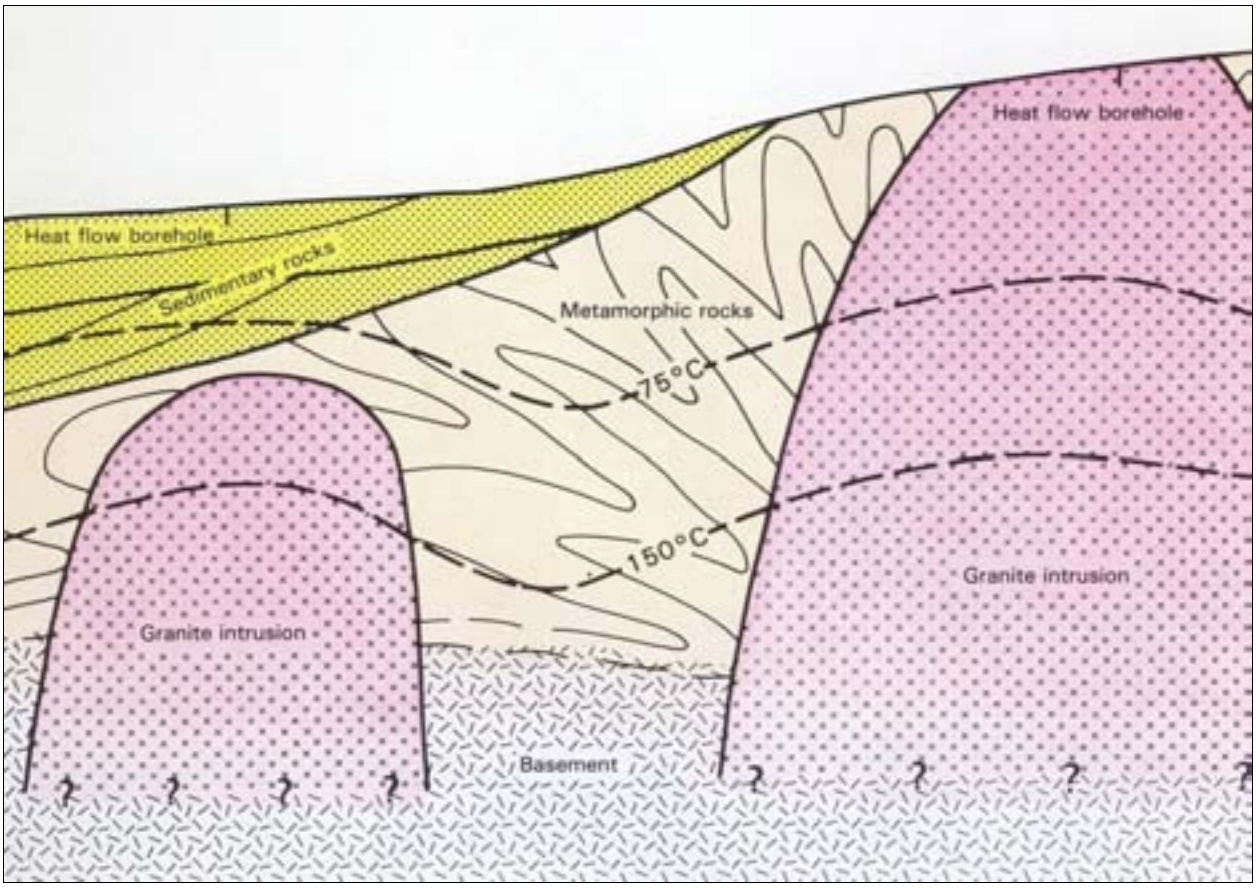


Figure 27 Diagram used on the front cover of all reports in the series ‗Investigation of the geothermal potential of the UK' (Downing and Gray, 1986), illustrating two contrasting concepts for HDR projects. On the right, an HHP granite intrusion extends from basement to outcrop (current surface), with no barrier to the upward flow of heat. On the left, an HHP granite intrusion is buried beneath a thick layer of low thermal conductivity sedimentary rocks, which will impede the upward flow of heat, causing it to pond and form a heat reservoir. In this case a thin layer of metamorphic rocks, into which the granite intrusions are emplaced, separates the top of the intrusion from the base of the sedimentary rocks. Superimposed isotherms illustrate the increase in geothermal gradient that would be associated with the two HHP granite intrusions relative to their country rocks. The intrusion on the right has lost some, or all, of its roof zone. The intrusion on the left has never been exposed and eroded; hence, it retains its entire roof zone. The diagram is not to scale, but the long side would be in the order of 20–30 km and the short side (depth) 15–20 km.

HHP granite intrusions can be exposed at Earth‘s surface or buried beneath other lithologies (Figure 27). In terms of their geothermal energy potential, the two settings have contrasting advantages and disadvantages: those exposed at the surface are easy to find and characterise, but the heat generated within and passing through them will have been dissipating into the atmosphere for many millions of years, and they may have lost much of their HHP rock through erosion; by contrast, those buried beneath other rocks will be difficult and relatively expensive to find and characterise, but they have the potential to yield far larger stores of geothermal energy because they may retain their original roof zone (which may be rich in radiothermal elements), and the overlying rocks may have impeded the upward flow of heat from them, with the result that a reservoir of trapped heat has developed. An example of one such ‗buried granite‘ setting that is currently being developed for geothermal energy (Cooper Basin, Australia) is described in Appendix 1.

The possibility of applying the HDR concept to exposed HHP granite plutons in Scotland was explored in the late 1970s and early 1980s. A summary of that project is presented below.

8.2.2 Previous investigation of HDR potential in exposed HHP granite intrusions

Introduction

A wide-ranging programme to investigate the geothermal potential of the UK was undertaken with government support in the late 1970s and early 1980s (results are summarised in Downing and Gray, 1986).

A heat flow map based on the Geothermal Map of the UK (BGS, 1986) shows the highest heat flow values in the UK to be associated with clusters of granite intrusions in the south-west of England, northern England, and the East Grampians region of Scotland (Table 3). Strongly negative anomalies in regional gravity data (which reflect changes in the density of rock in the crust) are associated with each of these areas (Figure 28), from which it is inferred that very large volumes (‗batholiths‘) of granite underlie each cluster of exposed intrusions: the Cornubian Batholith in south-west England, the Lake District and Weardale batholiths in northern England, and the East Grampians Batholith (sometimes referred to as the Eastern Highlands Batholith) in Scotland. In other words, the granite intrusions currently exposed at the surface in these areas appear to be just the surface expressions of much larger volumes of concealed granite that underlie each region.

The granite intrusions of Cornwall and Devon (which are of Carboniferous age and believed to be surface expressions of the Cornubian Batholith) were the first in the UK to be recognised as potential HDR targets (e.g. Dunham, 1974). An HDR research project funded by the then Department of Energy (DoE) and the European Commission was initiated in 1977 on the Carnmenellis granite intrusion in Cornwall, which has the highest known heat flow in the UK (~120 mW m^{-2}). The project, based at Rosemanowes Quarry, was essentially a rock mechanics investigation (involving deep drilling, fracture stimulation and flow-testing) of how to create a fractured reservoir (Batchelor, 1987; Richards et al., 1994); the intention was not to produce a power-generating system. The outcomes have been used in all subsequent EGS projects.

The potential of the HDR concept in Scotland was assessed (as part of the UK-wide assessment) through a collaborative investigation by IGS (now BGS), Imperial College and the Open University (Rollin, 1982, 1984; Lee, 1984; Webb and Brown, 1984; Wheildon et al., 1984; Lee et al., 1984, 1987). There are no known major Carboniferous granite intrusions in Scotland, and therefore no direct analogues of the south-west England intrusions. However, a moderately high heat flow value (95 mW m^{-2}) for the Early Devonian Weardale granite in northern England (England et al., 1980) focussed attention on other intrusions of similar age, of which there are many in Scotland (e.g. Brown et al., 1979). The East Grampians Batholith (EGB) is inferred to underlie an east-west trending zone extending inland from near Aberdeen as far west as Strathspey (Figure 28Figure 29). Many large granite intrusions of Silurian and Devonian age crop out within this zone (Figure 26), several of which have HP values well above the HHP threshold. Four intrusions (see below) were selected for detailed study; that study, which was part of a much wider programme of work carried out under the broad title ‗Investigation of the geothermal potential of the UK‘, is summarised below and is referred to hereafter as ‗the DoE HDR project‘.

The East Grampians intrusions

The Cairngorm, Mt Battock, Ballater and Bennachie granite intrusions were selected for detailed investigation in the DoE HDR project because they were considered to be the most promising HDR prospects in Scotland, based on their medium to large size, accessibility, and high HP values (Figure 26 and Table 12). Other intrusions with promisingly high HP values, notably the Monadhliath granite intrusion, were not included due to poor accessibility. All the intrusions underlie large upland massifs, and two – Cairngorm and Mt Battock – are among the largest at outcrop of any granite intrusions in Scotland (Table 11).

The four intrusions share many features. They consist of granite sensu stricto with subordinate proportions of coarser (pegmatitic) and finer (microgranitic and aplitic) granitic rock. Variations in grain-size and in the degree to which large crystals (phenocrysts) of feldspar are developed are characteristic features of all the intrusions, and this textural heterogeneity is the main basis for recognising and mapping internal divisions within the intrusions. Zones of rock that have been altered by hot water (hydrothermally altered rock) are common; these probably formed shortly after the granite magma was emplaced and solidified. The passage of hot water through these zones has produced a range of minerals formed by alteration (notably hematite, epidote and chlorite), veins of quartz, and joints. These act to weaken the rock mechanically, lower its thermal conductivity and raise its permeability.

Approach

The investigations focussed on characterising the thermal properties (HP, heat flow and thermal conductivity) and lithological character of the intrusions at and near the ground surface, modelling the extent and volume of granite at depth, and combining these datasets to produce modelled thermal profiles through the intrusions. A single vertical borehole was sunk to around 300 metres in each intrusion (Figure 29). Core was recovered from each borehole in three short (<7 metre) sections at approximately 100, 200 and 300 meters (amounting to ~5% of the total drilled depth). HP values for surface samples were affected by the fact that uranium is mobile in the surface and near-surface environment (leading to variations in measured uranium concentration that don‘t reflect those below the near-surface zone), so a second set of ‗preferred‘ HP values calculated from unaltered rock recovered in core discs and chippings was used for modelling. Heat flow values were calculated from depths below 100 metres in the boreholes, to avoid near-surface perturbations caused by the influx and movement of rainwater. The reported heat flow values incorporate a small correction for the effect of local topography, but a correction to account for the effect of recent climate change (see section 2.1.4) was not deemed necessary. The distribution of radioelements (K, U and Th) and the nature and possible origin of spatial variations in rock composition were assessed from whole-rock geochemical analyses of surface samples and core materials (Webb and Brown, 1984; Webb et al., 1985). The extent and shape of granitic rocks in the subsurface was modelled from gravity data (Rollin, 1984). Finally, thermal models drawing on all these data were generated, from which subsurface temperatures were predicted and HDR potential was assessed (Wheildon et al. 1984; Lee et al., 1984).

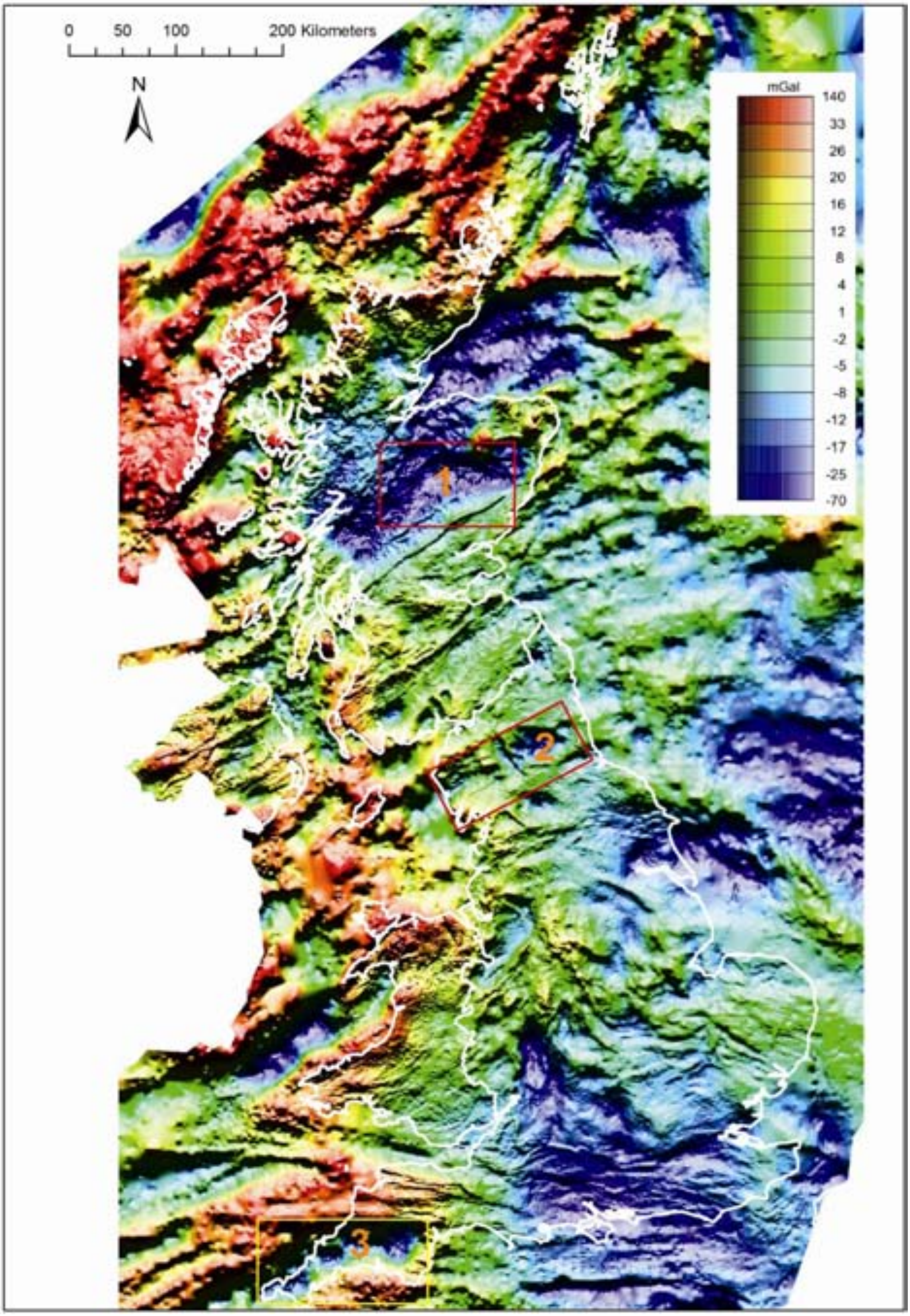


Figure 28 BGS colour shaded-relief image of the UK gravity field (Bouguer anomaly onshore, free-air anomaly offshore) illuminated from the north. 1– East Grampians Batholith, 2 – Lake District and Weardale batholiths, 3 – Cornubian Batholith.

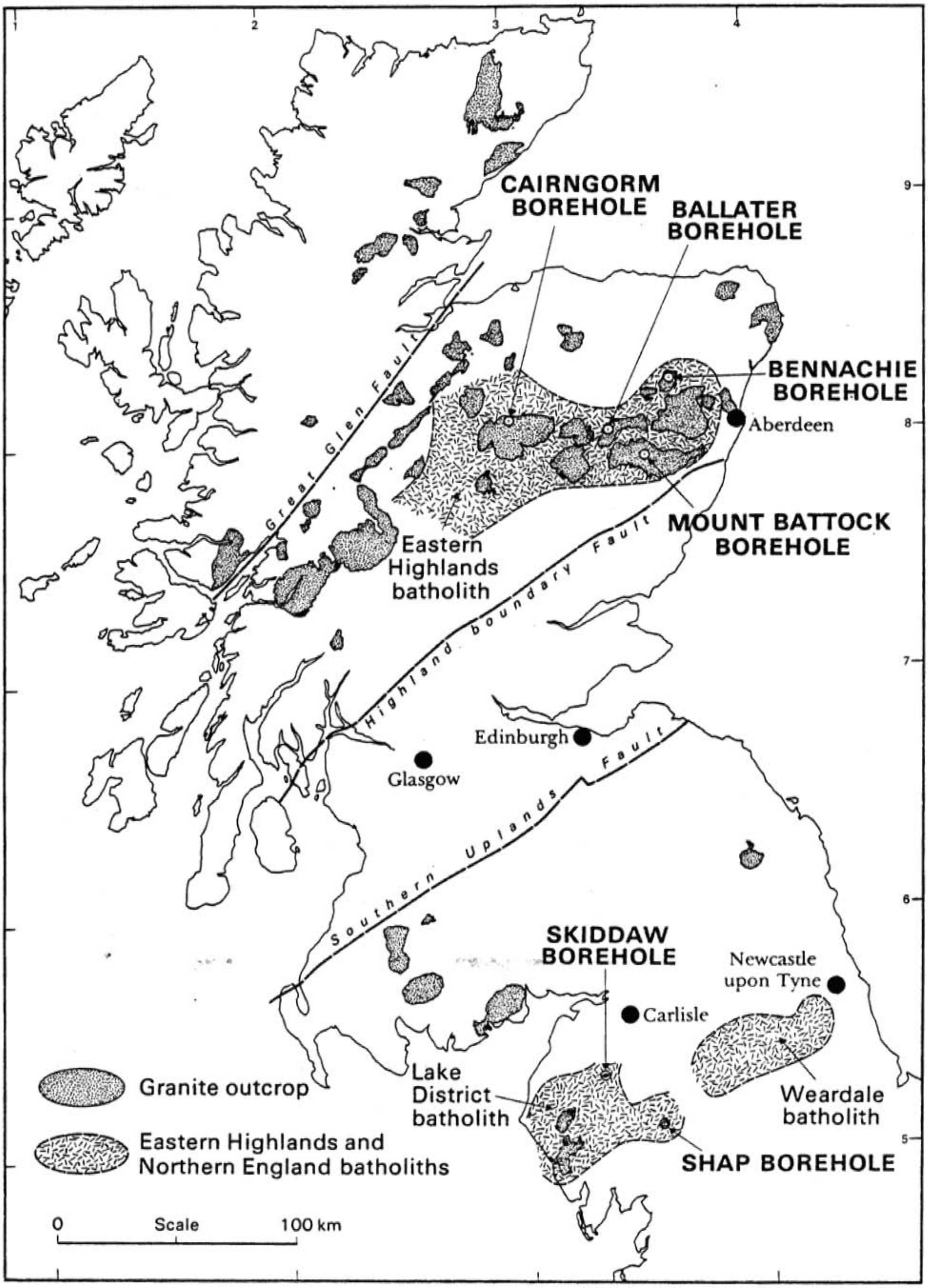


Figure 29 Inferred subsurface extent of the East Grampians Batholith (labelled ‗Eastern Highlands batholith' in this map), based on geophysical survey data. From Lee et al., 1984, Figure 1.4.

Results and conclusions

Thermal data for the East Grampians intrusions are summarised in Table 12, with comparable data for the other UK HHP intrusions that were included in the DoE HDR project. The East Grampians intrusions have the highest HP values but the lowest heat flow values; the heat flow values are only moderately elevated (~30% higher) with respect to the average value for the UK (54 ±12 mW m^{-2}; Wheildon and Rollin, 1986). The range of thermal conductivity values is broadly similar in all three areas, reflecting the fact that all the boreholes are in granite.

The association of promisingly high HP values and surprisingly low heat flow values in the East Grampians intrusions was interpreted to reflect two factors: (i) a decrease in HP capacity with depth that is much more rapid in the East Grampians intrusions than in the intrusions of northern and south-west England, and (ii) relatively low background heat flow in the region. The East Grampians Batholith is modelled from gravity data to be around 13 km thick (Rollin, 1984), ruling out a possible alternative explanation that granite only extends to a depth of 6–7 km. A rapid decrease in HP with depth was ascribed to rapid diminution in the concentrations of U, Th and K with depth; in other words, the HHP character of the intrusions was interpreted to be just a near-surface feature. This interpretation was based to a large extent on a theoretical understanding of granite magma evolution; the geochemical data provided by samples from the relatively narrow vertical range spanned by the borehole and surface exposures did not yield conclusive evidence to support the interpretation (Webb and Brown, 1984; Webb et al. 1985).

Region	**Pluton**	**HF** (1)	**HP** (2)	**TC** (3)
East Grampians	Cairngorm	69.5	7.3	3.5
	Mt Battock	58.7	4.8	3.0
	Ballater	71.4	6.8	3.2
	Bennachie	75.8	7.0	3.5
Northern England	Weardale	95.4	3.7	3.1
	Wensleydale	65.0	3.3	3.6
	Shap	77.8	5.2	2.9
	Skiddaw	100.9	4.2	3.5
South-west England	Carnmenellis (a)	116.2	4.1	3.3
	Bodmin (b)	116.1	4.2	3.3
	Land's End (c)	125.4	5.5	3.4
	St Austell (d)	126.2	4.2	3.3
	Dartmoor (e)	114.0	5.3	3.2

Table 12 Thermal data measured in boreholes and cores for selected UK HHP granites.

Modified from Table 8.1 in Lee et al. (1984). (1) HF = heat flow, in mW m^{-2}; (2) HP = heat production, in μW/m^{-3}; (3) TC = thermal conductivity, in Wm^{-1} K^{-1}; (a) mean of data from seven boreholes; (b) mean of data from five boreholes; (c) mean of data from three boreholes; (d) mean of data from two boreholes; (e) mean of data from five boreholes.

Models extending to a depth of thirty kilometres were generated from a combination of gravity data and both measured and inferred thermal property data for the granite intrusions and the surrounding rocks (Wheildon et al., 1984). In satisfying the measured HP and heat flow values at and near the surface, the models predicted temperatures of 85–98ºC at 5 km depth and 130–149ºC at 9 km. The geothermal gradient was therefore modelled to be approximately 17 ºC/km, approximately half that in the south-west England intrusions and much too low to yield a viable heat reservoir within an accessible depth range. On this basis, the authors concluded that the HHP granite intrusions of the East Grampians region should be ruled out as an HDR prospect.

8.2.3 Reassessment of HDR potential in exposed HHP granite intrusions

The conclusions of a brief review of the DoE-HDR project research into the East Grampians intrusions can be summarised as follows.

- Geochemical data from the East Grampians intrusions do not provide good evidence for strong vertical fractionation of radiogenic elements within the sampled depth range. However, field evidence suggests the present outcrop surface is close to the roof zone in each intrusion, so the concentrations of radiogenic elements in the East Grampians intrusions might therefore diminish quite rapidly below the present ground surface; however, the complexity of the magma emplacement history at the exposed levels (as revealed by detailed geological mapping of the intrusions since the DoE HDR project) means this may only become apparent over a vertical interval significantly greater than that penetrated by the boreholes (300 metres).
- HP values reported for other intrusions that are, in a geological sense, closely related to the four East Grampians intrusions are in the range 2.6–4.9 $\mu W/m^{-3}$. These intrusions appear to be exposed well below their roof zones, suggesting that HP capacity in the (concealed) main body of the East Grampians intrusions may decrease to within the range 2.6–4.9 $\mu W/m^{-3}$. Many of the granite intrusions of south-west England and northern England, which are associated with significantly higher heat flow values than the East Grampians intrusions, have HP values within this range. Hence, strongly vertically stratified U and Th content may account for the relatively high HP values in exposed parts of the East Grampians intrusions, but it probably does not explain adequately why heat flow values are significantly lower than those over the Cornubian and Lake District batholiths.
- The absence of reliable measurements of background heat flow in Scotland means it is currently not possible to confirm whether background heat flow is lower in the East Grampians region (or any part of Scotland) than in south-west England.
- Heat flow values determined from boreholes less than 2 km deep could be underestimated by up to 60%, because of the effect of climate change on the top part of the geothermal gradient, provides perhaps the most likely explanation for the relatively low heat flow values over the East Grampians Batholith compared to more southerly locations in the UK, and particularly south-west England which lies south of the limit of glaciation (see section 2.1.4).

Scotland lay towards the southern limit of the ice sheets, so the geothermal gradient may have been perturbed less here than in more northerly latitudes. An upward correction of 30% (half of the estimated maximum value of 60%) to account for the effects of climate change takes the heat flow value for the Cairngorm intrusion to 90 $mW\ m^{-2}$, significantly above the mean heat flow across all continents (65 $mW\ m^{-2}$), but still significantly below values for the south-west England intrusions. 90 $mW\ m^{-2}$ equates to a geothermal gradient of approximately 25ºC/km, which is significantly lower than that likely to yield a commercially viable heat reservoir at an accessible depth.

Thus, on the basis of existing heat flow measurements, the potential for developing commercially viable HDR projects within exposed granite intrusions in Scotland appears to be poor.

However, the borehole temperature data for boreholes sited in the East Grampians intrusions (and in crystalline rocks elsewhere in Scotland) sit on the trend defined by all borehole temperature data (Figure 9), raising the possibility that the temperature (and heat resource) at depth is significantly greater than is suggested by heat flow measurements. Exposed intrusions that are known, or suspected, to contain a significant volume of HHP granite should not therefore be ruled out as potential HDR prospects until the shape of the geothermal gradient below the climate-affected zone has been established in one or more deep boreholes. Based on surface HP capacity values and intrusion size at outcrop, the most promising intrusions are: Cairngorm, Bennachie, Ballater, Monadhliath, Fearn, Mt Battock and Helmsdale (Table 11 and Figure 30).

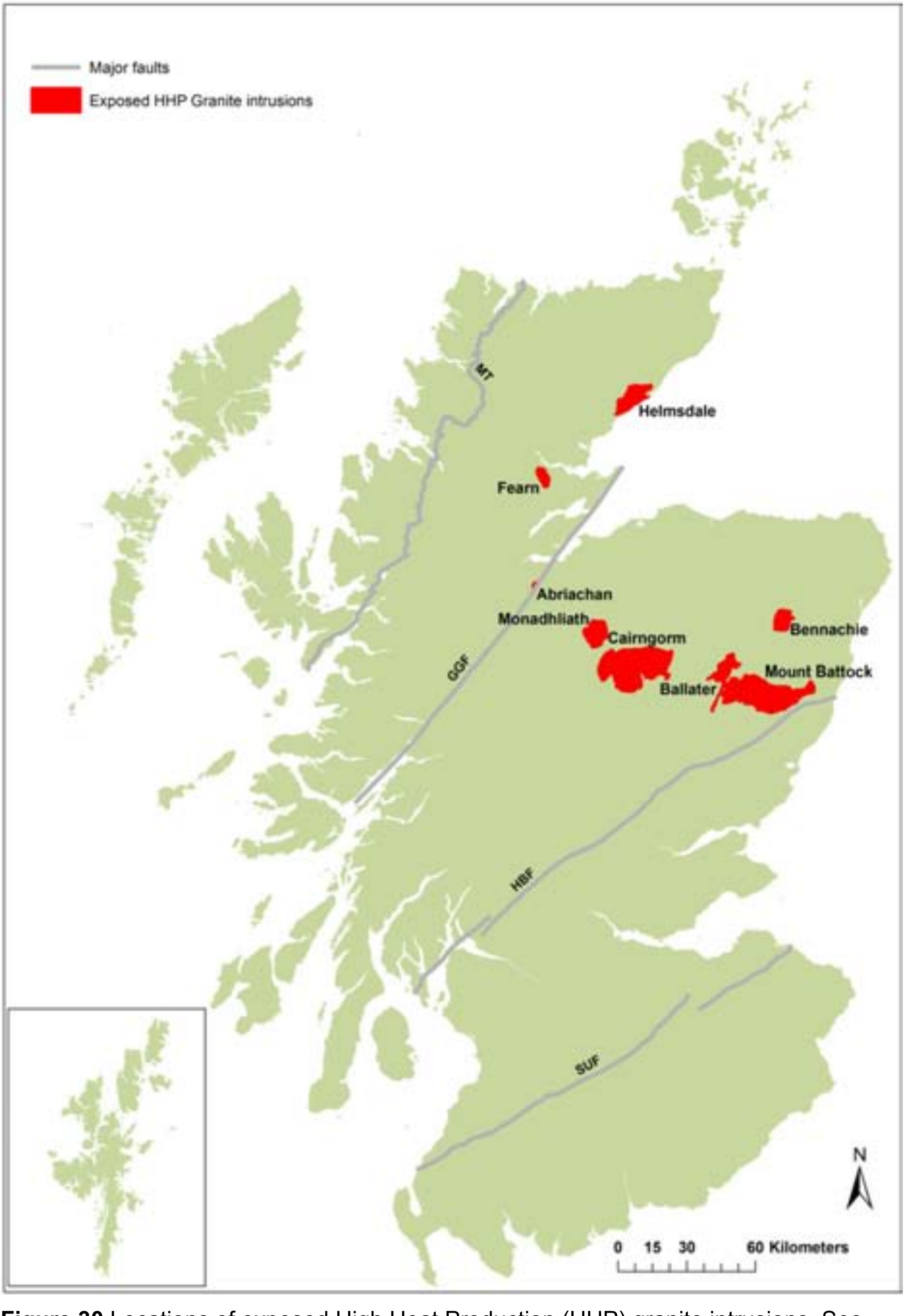


Figure 30 Locations of exposed High Heat Production (HHP) granite intrusions. See Figure 3 for abbreviations.

8.2.4 Buried intrusions of HHP granite

Introduction

The occurrence at outcrop in Scotland of intrusions with HP values at and above the HHP threshold raises the possibility that substantial heat reservoirs exist where HHP granite intrusions are buried beneath a thick cover of low thermal conductivity rocks.

To date, only two examples of buried large granite intrusions have been proved onshore in the UK: the Early Devonian Weardale and Wensleydale intrusions, both in northern England (Figure 29). Neither exceeds the 4 μW m^{-3} HP threshold used in this report to denote HHP character, but heat flow associated with the Wensleydale intrusion is similar to that in the East Grampians intrusions, and in the Weardale intrusion it is significantly higher (Table 12). The Weardale intrusion is inferred from geophysical data to consist of five connected masses of granite (Bott, 1967) and is concealed beneath several hundred metres of Carboniferous sedimentary rocks. The temperature in the top part of the intrusion is estimated to be higher by around 7ºC than the same granite would be at outcrop, because of the relatively shallow burial beneath low conductivity cover rocks (England et al., 1980). A modelled temperature profile, based on data gathered from the Rookhope borehole which penetrates the shallowest levels in the centre of the intrusion, predicted an average geothermal gradient between the top of the intrusion and a depth of 7 km of ~31ºC/km and temperatures of 150 to 200ºC between 4.4 and 6 km, respectively (Lee et al., 1984). More recently (in 2004), the UK‘s first deep (995 m) geothermal exploration borehole for more than 20 years was drilled at Eastgate in County Durham (Manning et al., 2007), penetrating 723 metres of the Weardale granite beneath 267 metres of Carboniferous strata (and the Whin Sill, a large sheet-like intrusion of dolerite). The extent to which heat has accumulated beneath the sedimentary rocks was not reported (it is likely to be relatively small given the thinness of the cover), but a reported relatively high mean geothermal gradient of 38ºC/km from the Eastgate borehole is likely, at least in part, to reflect the ‗buried hot granite‘ setting. The thickness of the sedimentary cover over these intrusions is much thinner than the 3–5 km that would probably be required of a major HDR prospect, but they illustrate well the concept and its potential.

Granite has a relatively low density compared to many other rock types, so large granite intrusions that are concealed in the subsurface may generate negative gravity anomalies that can be identified in regional geophysical surveys. The hot magma within an intrusion can affect the magnetic character of the rocks enclosing it, so concealed intrusions may generate positive magnetic anomalies that can also be detected by regional geophysical surveys. The following assessment of potential ‗buried hot granite‘ settings in Scotland (see Figure 31 for locations) is based largely on an assessment of current BGS bedrock geology maps, the BGS 1:500 000 series gravity and magnetic anomaly maps (BGS 1997; 1998), and the gravity modelling of Rollin (1984). The largest exposed HHP granites of the East Grampians Batholith (Cairngorm, Mt Battock and Monadhliath) are associated with positive magnetic anomalies of 150–350 nT and negative gravity anomalies.

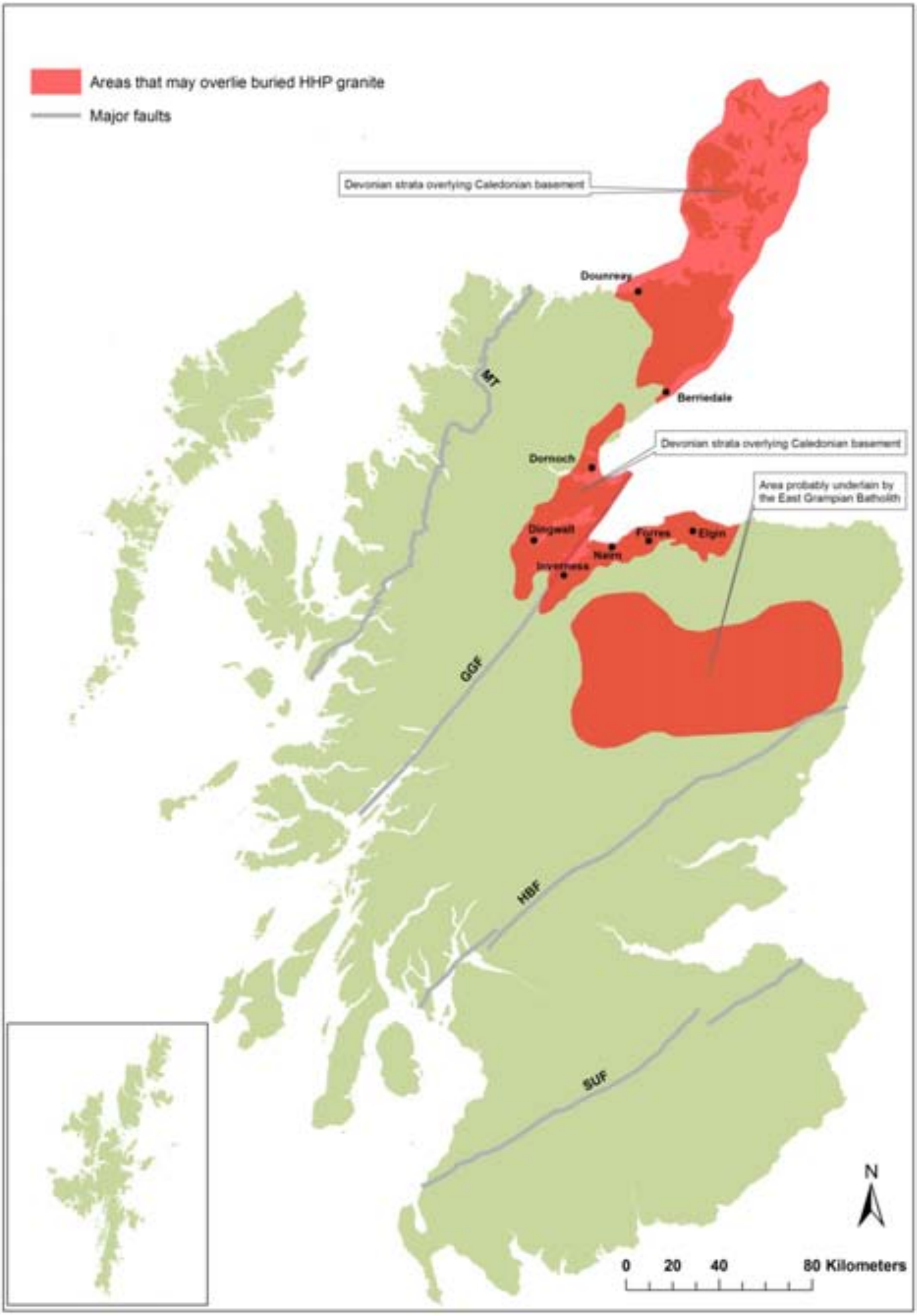


Figure 31 Onshore parts of Scotland considered most likely to overlie buried HHP granite intrusions. See Figure 3 for abbreviations.

The East Grampians Batholith

Using the BGS gravity anomaly map for the region and published rock density data for key rock types, Rollin (1984, Fig 5.1) generated a three-dimensional geological model of the Eastern Highlands region showing depth contours on the upper surface of the East Grampians Batholith (EGB) and nearby large intrusions of basic igneous rock. In the model, the top surface of the batholith undulates considerably and extends from above ground (in the exposed intrusions) to depths of more than 12 km below sea level. No substantial areas of non-crystalline (sedimentary) rocks overlie the modelled subcrop of the EGB, so the classic ‗buried hot granite‘ setting (low thermal conductivity sedimentary rocks overlying hot granite) does not exist here. Instead, the model shows granite underlying metamorphosed sedimentary rocks at a range of depths over a very large area. The thermal conductivity of the metasedimentary rocks (~3.5 Wm^{-1} K^{-1}) is broadly the same as in the granite (3.0–3.5 Wm^{-1} K^{-1}) (Wheildon et al., 1984), so it is unlikely that the metasedimentary rocks will act as an effective ‗thermal blanket‘ over the buried granite. However, the area encompassed by the model includes some settings with HDR potential:

(i) By analogy with the exposed East Grampians intrusions, parts of the concealed roof zone of the EGB may be affected by intense hydrothermal alteration (section 8.2.2). The hydrothermally altered rock is likely to have lower thermal conductivity than either the fresh granite or the overlying metasedimentary rocks, and if they are thick enough such zones may act to impede the upward transfer of heat across the interface between the granite and overlying metasedimentary rocks. Reservoirs of trapped heat may exist below (and within) such features. Hydrothermal fluids and radiogenic elements are likely to become concentrated in the topmost parts of intrusions, so modelled contours pointing to large circumscribed bulges at accessible depths on the surface of the concealed EGB would be obvious targets for further consideration. Before selecting target areas, a new 3D model of the region should be produced using up-to-date data, knowledge and interpretations.

(ii) Large intrusions of basic igneous rock crop out on the north side of the EGB; the Morvern–Cabrach, Insch and Huntly–Knock intrusions are the largest (Figure 32). These intrusions are believed to be laccoliths; that is, they are broadly flat-lying and saucer-shaped rather than upright and balloon-shaped (which is more typical of large intrusions). As such, the EGB will extend beneath them, and the interface between the intrusions and underlying rocks is likely to be relatively flat-lying (good for trapping heat). Like the EGB, the intrusions are enclosed in metasedimentary rocks. The basic igneous rock forming these intrusions has significantly lower thermal conductivity (~2.2 Wm^{-1} K^{-1}) than both granite and the enclosing metasedimentary rocks, so they have the potential to significantly impede the upward flow of heat supplied from beneath them. The northern margins of at least two exposed HHP granite intrusions – Ballater and Bennachie (Figure 26) – are in direct contact with the Morvern–Cabrach and Insch masses, respectively. The contacts are modelled (Rollin, 1984) to dip northwards at 45–60ºC, beneath a substantial thickness of basic rocks. The bases of the basic intrusions are modelled (Rollin, 1984) to be at between 1 and 5 km depth. Thus, HHP granite within the EGB may in places be concealed beneath a thick and extensive ‗cover‘ of basic igneous rocks in this region. As noted above, a new 3D model of the region should be produced using up-to-date data, knowledge and interpretations, before selecting areas for further investigation.

(iii) The subsurface extent of the EGB north-west of the Monadhliath intrusion was not well-constrained by the gravity modelling of Rollin (1984), but his modelling did suggest that it may continue sufficiently far north to underlie the Devonian sedimentary rocks that crop out around the margin of the Moray Firth (Figure 31). The area around Nairn and Forres, and possibly further to the east and west, may therefore be underlain by Devonian sandstones that overlie metasedimentary rocks, which in turn overlie granite in the EGB. A small granite intrusion in this area, the Auldearn intrusion, has compositional and textural characteristics similar to the East Grampians intrusions, and may be the surface manifestation of the buried EGB. Unfortunately, there is no reported HP value for the Auldearn intrusion. Intrusions of ‘hot’ granite buried beneath a thick cover of metasedimentary rocks and sandstone may exist in the district around Nairn and Forres.

The Orcadian Basin

In the far north-east part of Scotland a thick sequence of sedimentary rocks (sandstone, conglomerate and mudstone) was deposited in a large, lake-filled depression – the Orcadian Basin – during the Devonian Period, in the aftermath of the Caledonian Orogeny. The sedimentary rocks are now exposed onshore across the whole of Orkney, parts of Shetland, and within a variably broad band bordering the Moray Firth. They also occur offshore (mainly beneath younger sedimentary rocks) under much of the Moray Firth and farther afield. The thickness of sedimentary rocks generally increases towards the centre of the former lake, so the thickest onshore sections – possibly exceeding several kilometres (Rippon, 2002) – are probably mainly in the vicinity of the coast. The same crystalline basement rocks that underlie the Northern Highlands and Grampian Highlands underlie the Orcadian Basin strata, both onshore and offshore. Most of the exposed HHP granite intrusions in Scotland crop out on the mainland to the south and west of the Moray Firth (Figure 26 and Figure 30). The distribution of these exposed intrusions suggests that others are concealed beneath the strata of the Orcadian Basin.

Possible targets for ‘buried hot granite’ in onshore settings beneath Orcadian Basin strata include the following (in no particular order).

(i) The Orkney Islands. The islands are underlain mainly by Devonian sedimentary strata, though basement rocks crop out locally on Mainland. There is currently no geological evidence or geothermal evidence for buried hot granite. The sedimentary strata on Orkney include substantial thicknesses of mudstone, which has low thermal conductivity (Table 1) and should be a good thermal insulator.

(ii) Caithness, east of a line from Dounreay to Berriedale. The sedimentary rocks in this area are inferred to be underlain by a concealed granite intrusion, the ‘Caithness Granite’ (Hillier and Marshall, 1992). The available evidence suggests the intrusion was emplaced into the sedimentary strata (rather than having been buried beneath them), so it may be younger than the East Grampians and other late Caledonian intrusions. The sedimentary strata in Caithness are mainly mudstone, which has low thermal conductivity and should be a good thermal insulator.

Two large granite intrusions crop out in the metasedimentary basement rocks adjacent to this area: the Strath Halladale intrusion (Figure 26) has a very low HP value (1.4 μW m^{-3}), but the nearby Helmsdale intrusion (Figure 26 and Figure 30) has an HP value of 4.1 μW m^{-3} (above the HHP threshold used in this report). Uranium mineralisation occurs at the contact between the Helmsdale granite and the Devonian sedimentary rocks that overlie it locally, and it is not clear to what extent the measured HP value (from samples collected at the ground surface) has been influenced by leaching and local redistribution of uranium. The pink, texturally variable granite at Helmsdale is similar in many respects to that in the East Grampians intrusions, but unlike them the Helmsdale intrusion is apparently concentrically zoned and lacks significant hydrothermal alteration. These features suggest the outcrop level through the Helmsdale intrusion is below the roof zone, hence the measured HP value may be broadly representative of a substantial volume of rock at depth. The Helmsdale intrusion is interpreted to be a steep-sided, stock-like mass, and is associated with a significant positive magnetic anomaly (~150 nT), similar in magnitude to the anomalies associated with the HHP granites of the East Grampians Batholith. North of Helmsdale, a slightly larger (~180 nT) magnetic anomaly centred on the coast just south of the town of Wick, well within the outcrop of the Devonian strata, may point to a concealed, Helmsdale-like intrusion (e.g. Flinn, 1969). Heat flow has been measured in several boreholes near to this magnetic anomaly (Figure 4); the values lie close to the UK mean (54±12 mW m^{-2}; Wheildon and Rollin, 1986).

(iii) The area bounded roughly by Dornoch in the north, Dingwall and Inverness in the south, and Elgin in the east. Two granite intrusions with HHP character - Fearn (HP = 5.1 μW m^{-3}) and Abriachan (HP = 4.0 μW m^{-3}) (Figure 30) – crop out in metasedimentary basement rocks close to this area (Figure 26) suggesting there is a reasonable prospect of at least one buried intrusion of HHP granite in the area. A substantial positive (~350 nT) magnetic anomaly extending from Ben Rinnes to Elgin and northwards beneath the Moray Firth is the most striking in the Eastern Highlands area (Rollin, 1984). This magnetic feature is not associated with a strong positive gravity anomaly and is therefore probably not a body of basic igneous rock. It could reflect a large, buried body of granitic rock (Rollin, 1984).

Midland Valley

The Midland Valley represents the largest onshore area in Scotland where a thick pile of sedimentary rocks overlies crystalline basement. The sedimentary strata in places contain numerous seams of coal, which has very low thermal conductivity (Table 1) and so is an excellent thermal insulator. The coal seams are, however, very thin compared to the interbedded mudstones and sandstones that will mainly determine the thermal conductivity profile, and the degree to which they would act as a thermal insulator is not clear. The nature of the basement rocks beneath the Midland Valley is very poorly understood, and the extent to which intrusions of granite (let alone HHP granite) might exist in them is not known, and may be impossible to determine. Only one intrusion of granitic rock of significant size actually crops out within the Midland Valley; the Distinkhorn intrusion (Figure 26) consists of diorite and granodiorite, and has low HP capacity (2.0 μW m^{-3}). The potential for locating and exploiting a ‗hot buried granite‘ in the Midland Valley therefore appears to be very small; however, if granite intrusions do exist in the basement rocks, the heat they supply to the overlying sedimentary rocks may contribute to the geothermal energy potential in Hot Sedimentary Aquifer settings and abandoned mine workings.

Southern Uplands

A north-east–south-west trending gravity anomaly near Peebles in the north-east part of the Southern Uplands region has been interpreted to reflect a large, concealed granitic intrusion (the ‗Tweedale Granite‘) whose top lies beneath 2–3 km of weakly metamorphosed sedimentary rocks (Lagios and Hipkin, 1979; Rippon, 2002). By analogy with the large intrusions that crop out further to the west (Loch Doon, Fleet and Criffel, Figure 26), at least part of the inferred Tweedale Granite could have HHP character. The metasedimentary rocks of the region have thermal conductivity values similar to those of granite, and will not significantly impede the upward flow of heat generated beneath them.

In the south-west part of the Southern Uplands, moderately thick piles (probably <1,500 metres) of Permian age sandstones and subordinate basic igneous rocks are preserved in several areas (see section 7.3.1.1). These sequences might act to impede the upward flow of heat from beneath them, but their relatively small size suggests they are unlikely to overlie intrusions of granite.

8.3 LOW THERMAL CONDUCTIVITY ROCKS IN AREAS OF ELEVATED HEAT FLOW

For any given heat flow value, units of low thermal conductivity rocks should be hotter than units of high thermal conductivity rocks, yielding a broadly consistent geothermal gradient. Thick units of low thermal conductivity rocks therefore have the potential to contain large reservoirs of heat. This effect will be enhanced if the supply of heat from depth exceeds normal ‗background' values. Two areas of Scotland where this setting may exist are described below (Figure 32).

Basaltic and andesitic lavas form thick units of low thermal conductivity rocks (probably around 2.2 $Wm^{-1} K^{-1}$) on Skye, Mull, in neighbouring Morvern, in Lorne (Argyll), the Midland Valley, and around Cheviot in the Southern Uplands. Elevated temperatures compared to other rock types may exist in these units due to their low thermal conductivity. One of these areas may be associated with slightly elevated background heat flow. The western seaboard of Scotland (together with Northern Ireland) was the last part of the UK to suffer a geological event that involved the transfer of a substantial amount of heat from the mantle into the crust; this occurred during the opening of the North Atlantic Ocean, around 60 million years ago. The resulting voluminous magmatism created many intrusions, volcanic centres and thick piles of lava, which now crop out extensively on islands of the Inner Hebrides and in numerous offshore locations. Residual heat from this event, stored deep in the crust, may provide a small boost to background heat flow in the area. A preliminary assessment by BGS of thermal data from the Atlantic Margin (BGS unpublished work) has identified no evidence for residual heat flow associated with Tertiary volcanism; however, a more detailed assessment would be required to confirm this preliminary outcome.

The low thermal conductivity (~2.2 $Wm^{-1} K^{-1}$) of basic (silica-poor) igneous rocks forming large intrusions in Aberdeenshire (including the Morvern-Cabrach, Insch and Huntly-Knock intrusions that were described in section 8.2.4), means they may be hotter than rocks of higher thermal conductivity in the same area. As described in section 8.2.4, these intrusions are interpreted to overlie the East Grampians Batholith, with their bases at between 1 and 5 km depth. Parts of the EGB consist of HHP granite, and might provide a boost to background heat flow in the area.

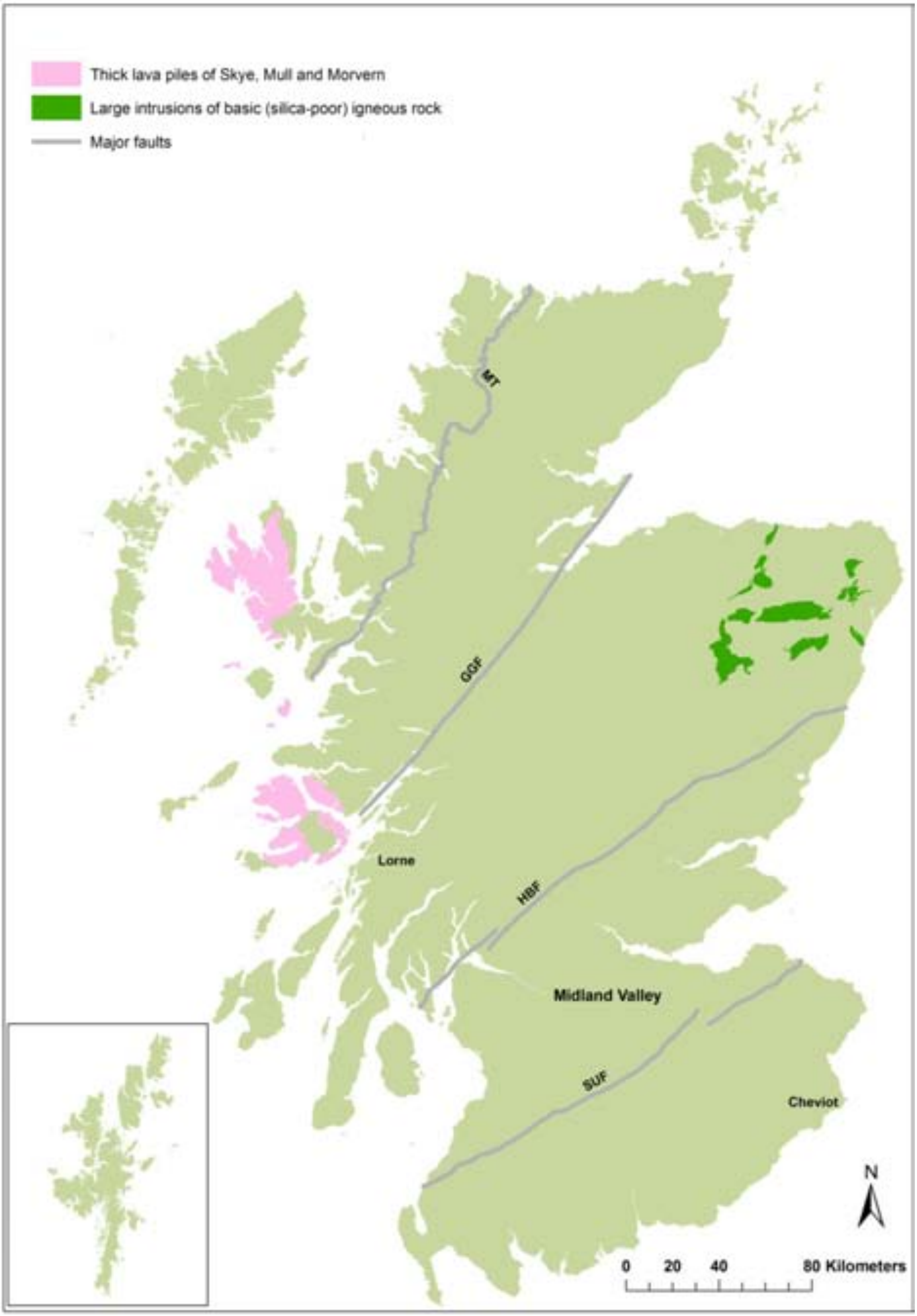


Figure 32 Onshore parts of Scotland where large, thick units of low thermal conductivity rocks crop out at the surface. These rock units may contain HDR prospects. See Figure 3 for abbreviations.

8.4 GEOTHERMAL POTENTIAL IN LOW PERMEABILITY SEDIMENTARY ROCKS

The ‗regional geothermal gradient‘ derived from data plotted on Figure 9 suggests that a temperature of 100°C should be encountered at approximately 3,000 metres, and 150 °C at approximately 4,000 metres, in parts of Scotland where sedimentary rocks extend to such depths. The same temperatures would be encountered at around 3,300 metres and 4,900 metres respectively if the lower geothermal gradient of 30.5°C/km obtained from onshore boreholes is applied. To date, no onshore boreholes in Scotland have penetrated sufficiently far into the crust to test whether the permeability required for HSA potential is preserved at such depths. However, if the estimated temperatures do exist the geothermal resource may be sufficiently large at accessible depths to have Hot Dry Rock potential if the rocks are insufficiently permeable to have HSA potential. Based on current knowledge, sedimentary rocks extend to depths exceeding 3,000 metres in most of the Midland Valley and possibly around the edges of the Moray Firth.

8.5 CONCLUSIONS

1. The widely quoted practical lower depth limit for exploiting HDR resources is 5,000 metres. The ‗regional geothermal gradient‘ for Scotland suggests that temperatures of around 150°C should occur widely around, or slightly above, this depth, hence rocks with HDR/HWR potential may underlie many parts of the country. However, the HDR/HWR concept is most suited to crystalline rocks, and the lack of temperature data for crystalline rocks in deep (> 2 km) onshore boreholes means that caution should be exercised in applying the regional temperature gradient described in this report to potential HDR/HWR resources in crystalline rocks.

2. Some parts of the crust contain thermal anomalies, wherein the size of the local heat resource exceeds that which is produced by simple ‗background‘ heat flow. Finding thermal anomalies at accessible depths should increase the chance of developing viable Hot Dry Rock/Enhanced Geothermal System schemes, because the average geothermal gradient in the crust overlying them is higher than the ‗background‘ gradient. In Scotland, thermal anomalies in crystalline rocks might be produced in three settings: (i) where the background heat flow is augmented by additional heat generated in situ; (ii) where the upward flow of heat is impeded, such that some of it becomes trapped; and (iii) a combination of (i) and (ii).

3. Intrusions of granite containing elevated concentrations of radiothermal elements (U, Th, K) are likely to be the only source of significant additional heat generated in situ within the crust beneath Scotland (setting (i) in conclusion 2). Seven large High Heat Production (HHP) granite intrusions are exposed in Scotland; a cluster of intrusions lies in the East Grampians region and two others crop out in ground to the north of Inverness. A previous investigation of the East Grampians intrusions concluded that the heat flow values associated with them were too low to indicate HDR potential. However, the recent recognition that heat flow values in Scotland probably significantly underestimate the size of the heat resource at depth (conclusion 3) indicates that the geothermal potential of exposed HHP granite intrusions should be re-assessed (ideally with new heat flow data).

4. The presence of exposed HHP granite intrusions in parts of Scotland raises the possibility that substantial heat reservoirs exist where HHP granite intrusions are buried beneath a thick cover (blanket) of insulating low thermal conductivity rocks. Such settings may exist in Orkney, Caithness, and the coastal zone to the north and east of Inverness, where Devonian sedimentary rocks overlie Caledonian

basement (in which reside all of the exposed HHP intrusions). Much of the East Grampians region is underlain at depth by the inferred East Grampians Batholith. Some parts of the buried batholith may have HHP character, and the batholith is in places overlain by large, variably thick intrusions of silica-poor igneous rock with low thermal conductivity. Unfortunately, the buried setting and the 'thermal blanket' effect of the low conductivity rocks means that good 'buried hot granite' prospects are likely to be difficult to identify using only near-surface and remotely-sensed data.

5. Some thick rock units with low thermal conductivity might impede the upward flow of heat sufficiently to create reservoirs of trapped heat (setting (ii) in conclusion 2). This effect will be enhanced if the supply of heat from depth exceeds normal 'background' values. Such a setting may exist in two parts of Scotland. (i) Residual heat from the Tertiary opening of the North Atlantic Ocean may provide a small boost to background heat flow along the western seaboard, parts of which (Skye, Mull, and neighbouring Morvern (Figure 32) are underlain by thick piles of low thermal conductivity lavas. A preliminary assessment by BGS of thermal data from the Atlantic Margin (BGS unpublished work) has identified no evidence for residual heat flow associated with Tertiary volcanism; however, a more detailed assessment would be required to confirm this preliminary conclusion. (ii) Some of the large, low thermal conductivity, silica-poor intrusions in Aberdeenshire are interpreted to overlie the East Grampians Batholith, with their bases at between 1 and 5 km depth. Parts of the EGB consist of HHP granite, and might provide a boost to background heat flow in the area.

8.6 RECOMMENDATIONS

The evidence base for assessing the potential for Hot Dry Rock prospects in Scotland is far from adequate. Most significantly, our knowledge of the distribution of granite intrusions with HHP character is limited to those that are currently at outcrop in onshore areas and for which appropriate geochemical data exist. We need therefore to improve our understanding of the distribution in Scotland of exposed and buried intrusions containing HHP granite. The following suggestions for further work focus mainly on identifying and characterising intrusions of HHP granite.

R9 Compile heat production data for all the granite intrusions of Scotland to identify all intrusions that have HHP character at outcrop

A programme of systematic surface sampling and geochemical analysis to augment the existing dataset would provide a complete dataset for granites across Scotland.

R10 Conduct research to identify whether some of the exposed intrusions that do not have HHP character would have had HHP character in now-eroded portions, or may have HHP character in still-buried portions

This would help to constrain the true areal distribution of granite intrusions with HHP character, and to establish whether buried HHP granite intrusions may exist in parts of the country beyond those in which they currently crop out. This could be addressed by: (i) developing a fuller understanding of how and why HHP granite forms; (ii) establishing the typical position and proportion of HHP rocks in intrusions; and (iii) identifying a geochemical (or some other type of) 'fingerprint' that can be used in intrusions lacking HHP character at outcrop to point to the presence of HHP rocks in eroded or concealed parts. A detailed study of intrusions in Scotland and elsewhere could address these issues, drawing on the vast body of published and unpublished granite literature, and gathering new data where necessary.

R11 In offshore areas, use seismic survey data and information from wells to identify buried intrusions and intrusions exposed on the sea floor

This would help to constrain the true areal distribution of granite intrusions.

R12 In onshore areas, re-interpret existing regional geophysical data and 3D geological models using modern methodologies and up-to-date knowledge of the surface and subsurface geology to identify possible buried granite intrusions (and other potential HDR settings)

Specific objectives could include: (i) improving the existing model of the 3D shape of concealed parts of the East Grampians Batholith and low thermal conductivity units that overlie it, and their spatial relationships; (ii) improving the characterisation of known geophysical anomalies that may point to granite intrusions concealed beneath Old Red Sandstone strata; (iii) identifying and characterising other locations where granite intrusions may be concealed beneath several kilometres of sedimentary rock. New, higher-resolution geophysical data collected from a subset of carefully selected prospects would provide a clearer picture of the size, depth, shape and lithology of buried units, and their spatial relationship with overlying rocks.

R13 Characterise the fracture network in exposed HHP intrusions

The ‗buried granite‘ model relies on heat building up over many millions of years beneath a low thermal conductivity layer, but if the granite contains a system of open, connected fractures (which typically form in unroofed granite intrusions) it could suffer significant heat loss via lateral fluid flow. Furthermore, the orientation and disposition of the existing fracture network within an intrusion plays a major role in controlling the shape and nature of an engineered reservoir. A study of fracture patterns in exposed HHP granites could provide an indication of the fracture architecture that will be encountered in geothermal reservoirs developed in buried intrusions.

R14 Conduct a programme of deep drilling

Ultimately, one or more deep boreholes will have to be sunk onshore if the potential for exploiting deep geothermal energy in an onshore setting is to be evaluated fully. There are no zones of unusually high heat flow and no existing deep onshore boreholes in Scotland, so finding an accessible deep HDR geothermal resource will require a dedicated exploration programme. Initially, our ability to identify and quantify geothermal energy prospects will depend on gathering thermal data at the surface and in shallow boreholes, and on building models of the geology in three-dimensions from surface-based and remote-sensing surveys. However, at some point a deep drilling programme will be needed to provide measured and observed, factual data. To provide a clear indication of the deep geothermal regime, and in particular the shape of the geothermal gradient beneath the influence of surface- and near-surface effects, a deep geothermal borehole would probably need to extend to a depth of at least 3 kilometres, and ideally to 5 kilometres.

Appendix 1 The Scottish National Minewater Potential Study and the Shawfair Minewater Project

The Scottish study was done by PB Power (Energy Services Division) for Midlothian Council (PB Power, 2004). The report states that the study was based on existing geothermal surveys, although it doesn‘t reference these. Although the title of the report is the Shawfair Minewater Project, the subtitle (Scottish National Minewater Potential Study) and the report content make it clear that this study considered the potential for minewater heating at Shawfair in the context of the potential across the Midland Valley of Scotland.

Both the specific potential at Shawfair and the wider potential are summarised here.

THE SHAWFAIR MINEWATER PROJECT

Shawfair is the name of a planned new town to be built largely on the site of the former Monktonhall colliery in Midlothian, south-east of Edinburgh and currently on hold due to economic conditions. It overlies substantial former coal mine workings. Early in the development plans for Shawfair there was considerable interest in the use of minewater and heat pump technology to supply a community heating scheme (e.g. Banks et al., 2003; PB Power, 2004; Malolepszy et al., 2005; McLoughlin, 2006). The PB Power feasibility study on the resource potential, energy demand and technological options for the site concluded that there was potential for such a scheme, and a successful grant application to the EC was made in 2003 with £3.5 million being awarded. However, further funding applications by Midlothian Council from UK and Scottish government sources (McLoughlin, 2006) failed when the business case for the mine water heating scheme could not be successfully concluded, in part due to issues of the ownership of the resource, and the plans for using mine water at Shawfair have been abandoned (Minewater Project, 2009).

The Coal Authority has an ongoing commitment to pumping mine water from Monktonhall to control mine water levels (Coal Authority pers.comm.). Monktonhall Colliery originally had an 11 km^2 footprint accessed by two 1,000 m deep shafts. The temperature at 1,000 m depth is some 25°C and the feasibility studies suggested that sustainable pumping of mine water at 16°C would be possible (Banks et al., 2003). A heat pump could raise this temperature to between 40 and 60°C. Waste mine water exiting the heat pumps at around 8°C could be re-injected to the mine periphery and/or at a level below the abstraction point in a nearby shaft, or could be discharged at surface to reed bed water treatment facilities, or used for other purposes such as cooling or grey water (Banks et al., 2003; PB Power, 2004). Other options could have been the separate abstraction of shallower, cooler water for use in cooling installations, leading potentially to seasonal manipulation of the mine water and thermal energy storage in the flooded mine workings (Banks et al., 2003). The studies raised concerns about mine water quality, specifically the high iron content, and its potential corrosive and encrustation effects on heat exchangers (Banks et al., 2003).

THE SCOTTISH NATIONAL MINEWATER POTENTIAL STUDY

The Scottish National Minewater Potential Study (PB Power, 2003) reviewed rebounding water level monitoring data, provided by the Coal Authority and their consultants, IMC Consulting Engineers Ltd, for closed coal mines in Scotland in order to estimate the potential thermal resource available from the old mine workings. The monitoring data were originally collected to ascertain the rates and influence of rebounding water levels in the mines, not for the purpose of estimating available thermal energy (PB Power, 2004). Most of this study concentrated on the heat demand and economic cost of mine water heating schemes: only approximately 16 out of 153 pages deal with the technical potential of mine water for heating.

The report identifies more than 60 underground coal mine locations in Scotland and categorises them as follows (PB Power, 2004):

1. Sites with a pumping system already installed to manage groundwater levels and discharge.
2. Sites with a known discharge by gravity and natural flows.
3. All other sites where drilling and deep pump installations would be needed to create a mine water circulation system.

The report states that the deepest mine workings have virgin rock temperatures of about 37 to 40 °C, and that the water in the deepest parts of the mines may well be close to the maximum rock temperatures, but that near to shafts, natural convection systems will destroy the thermal convection (PB Power, 2004). It is not clear if this agrees with other reports that the water temperature at approximately 1 km depth (e.g. in Monktonhall) is approximately 25°C (Banks et al., 2003), or with other data collected recently by BGS. However, the remainder of the report assumes that the mixed water temperature delivered to heat pumps is not more than 13°C, which is typically equivalent to water abstracted through boreholes or shafts (i.e. categories 1 and 3, above) from 100 m depth (PB Power, 2004). This is acknowledged as probably a conservative estimate. No thermal data are available for Category 2 (gravity) discharges, but it is assumed that temperatures will be lower than pumped discharges, possibly around 10°C (PB Power, 2004). This is supported by a single temperature measurement of gravity mine water drainage taken during a separate BGS project into groundwater chemistry (Baseline Scotland), which was 9.8°C.

Estimates of the potential flow rate of mine water from the mines were made based on records of the numbers of men known to be employed underground during mine operation. Additional information was obtained on mine size and interconnectivity, although the report doesn‘t make clear how detailed this information was compared to what may potentially be available, nor how it was used in the estimate of mine water flow rate.

Estimates of heat resource were then made from estimates of the flow rate of mine water. The conversion factor for the Monktonhall site was 16.75 litres/second (l/s) mine water flow per 1000 kWth (kilowatt thermal) (PB Power, 2004). It isn‘t clear if the same factor was used for all the examined mines in the study.

Issues related to mine water chemistry, solids content and corrosion / precipitation potential were not considered in detail, but most potential problems of this nature were assumed to be treatable given available technology (PB Power, 2004).

The report provides maps of identified collieries, pumping sites and/or gravity discharges in Scottish coalfields, and information on the pumping and/or discharge flow rates from each. Most of the larger sites and flows are in the east side of central Scotland, but smaller schemes are present throughout former coal mining areas (PB

Power, 2004). The report recommends that category 1 and 2 sites should be developed first, because the mine water resources have already been proved and the risks are therefore lower.

The study then combines these assessments / estimates of mine water flow with a detailed assessment of the heat demand and economic costs of developing heating schemes at each of the identified abandoned mine sites. Based on this, it provides a list of the ten preferred sites for developing mine water heating schemes in Scotland (Table 2), with the thermal resource interpreted from the estimated flow rates. The total estimated heat capacity of the ten sites is 83 MW. It is noted that the economic ranking of sites varies depending on the technology option selected and the discount rate applied; that sites where there is little or no current heat demand are not ranked highly (e.g. Monktonhall); and that more detailed evaluation may show that the two smallest sites in this list would prove to be less economically viable than some of the larger ones (PB Power, 2004). Most of these too are in the east of the Midland Valley; only two (including one of the smallest) are in the general Glasgow area (in Motherwell).

Postcode	**Site**	**Mine water Thermal Resource (kW)**[1]
EH19	Lady Victoria	9450
EH22	Lingerwood	1890
EH47	Polkemmet	9450
EH51	Kinneil	11340
FK10	Manor Powis	7560
KA9	Auchincruive	5670
KY1	Seafield	11340
KY12	Blairhall, Bogside and Valleyfield	17010
ML2	Overtown	1890
ML7	Kingshill No 1 and 3	7560

Table A2 The ten preferred abandoned Scottish coal mines for mine water heating schemes (from PB Power, 2004)

Appendix 2 Existing mine water schemes in Scotland

The following information is extracted from Ó'Dochartaigh (2009).

There are only two known current schemes in Scotland that use mine water as a source of heat: one at Shettleston in east Glasgow and one at Lumphinnans in Fife. Both were at least partly designed by John Gilbert Architects (http://www.johngilbert.co.uk/).

SHETTLESTON, GLASGOW

This open loop ground source heat scheme was completed in 1999 and serves 16 new-build dwellings (two storey houses and two/three storey flats). The heating system is based on mine water from flooded coal mine workings in the Glasgow Ell Seam beneath the site, which is abstracted via a borehole approximately 100 m deep. Mine water at 12 °C is circulated through a water-to-water heat pump, heating water to 55°C which is output to an insulated thermal storage tank with 10 m^3 volume. The hot water in this tank is supplemented by a side loop to 36 m^2 of solar collector panels which gives additional energy gain to the thermal tank, mostly in the afternoon: from the available details, however, it doesn't seem that these solar panels provide a large proportion of the supplied heat. From the thermal store, water is distributed to hot water central heating radiators and through closed exchanger coils to domestic hot water storage cylinders (which are fitted with electric immersion heaters to further boost water temperature if necessary). The total annual heating and hot water cost per dwelling is £90–£100 (Banks et al., 2003, Banks et al., 2008).

Waste water from the system is discharged below the water table via a shallower re-injection borehole, at 3°C (Banks et al., 2008).

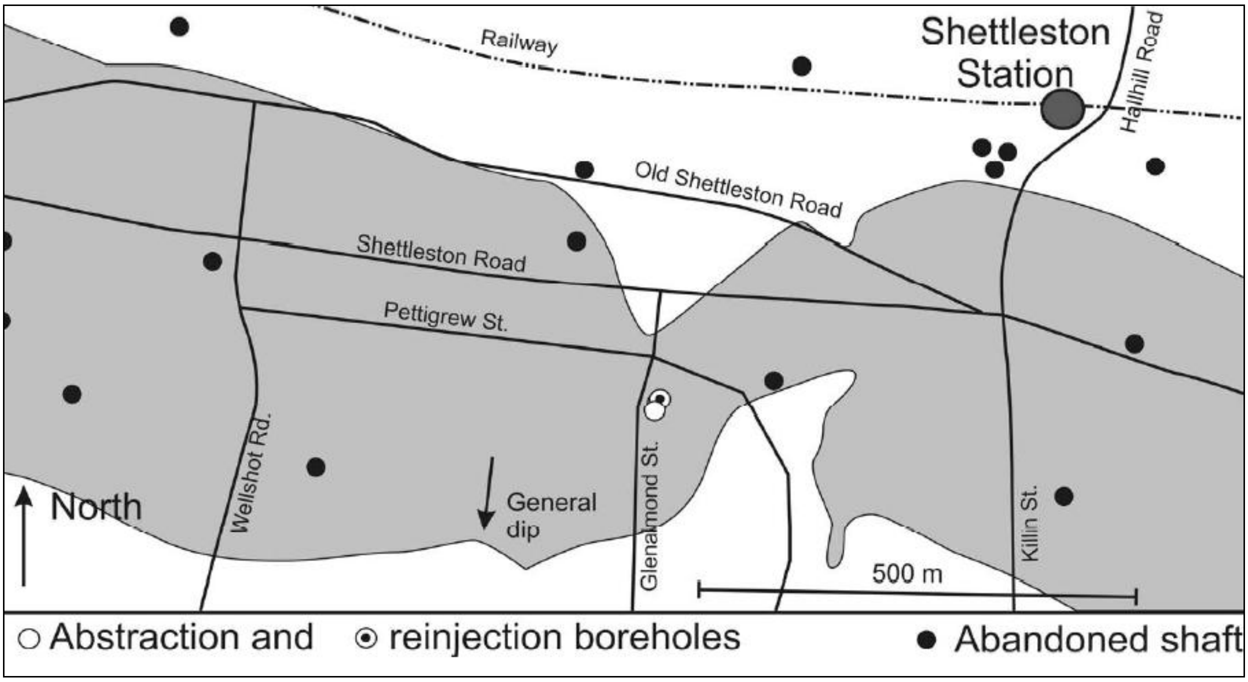


Figure A1 Map illustrating workings in the Ell Coal Seam below the Shettleston ground source heat scheme in east Glasgow, with sites of abandoned shafts and the abstraction and re-injection boreholes of the scheme also marked (diagram from Banks et al., 2008 / Holymoor Consultancy)

LUMPHINNANS, FIFE

This open loop ground source heat scheme was retro-fitted to a 1950s apartment block of 18 dwellings, and completed in 2000/01. Mine water is pumped from flooded coal mine workings in the Jersey / Diamond seam beneath the site via a 172 m deep borehole. The temperature of the pumped mine water is variously reported as 12°C (Banks et al., 2008) or 14.5°C (Banks et al., 2003). It is circulated through a water-to-water heat pump, heating water to 55°C which is output to a thermal storage tank. This feeds domestic hot water (which also includes supplementary immersion heaters) and central heating systems (Banks et al., 2003; Banks et al., 2008).

Waste water at 3°C is returned to a permeable stratum above the flooded workings from which water is abstracted, via a shallower re-injection borehole some 100 m away from the abstraction borehole (Banks et al., 2003).

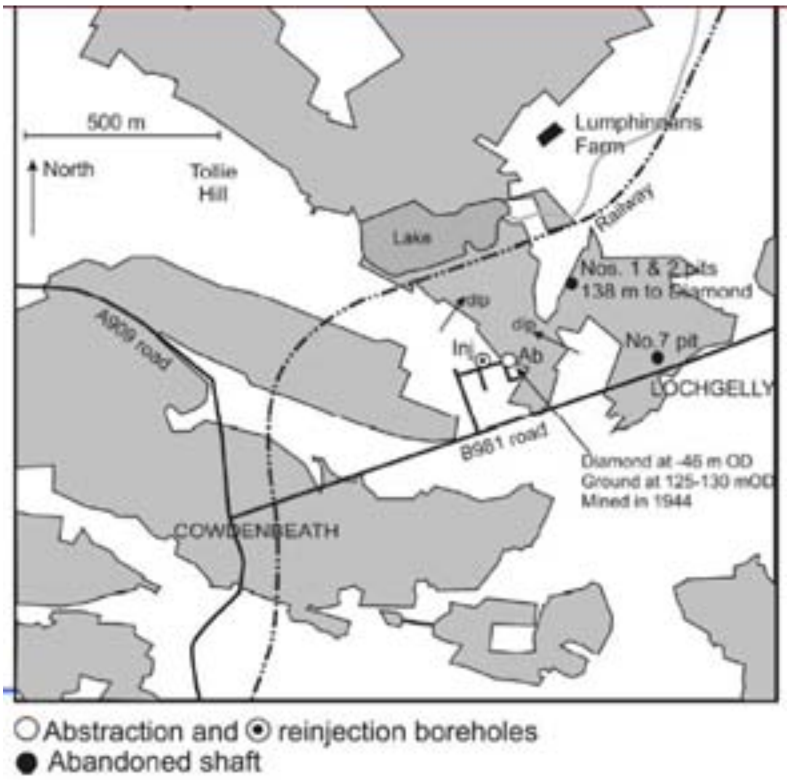


Figure A2 Map illustrating workings in the Jersey / Diamond coal seam beneath the Lumphinnans ground source heat scheme in Fife, with sites of abandoned shafts and the abstraction and re-injection boreholes of the scheme also marked (diagram from Banks et al., 2008 / Holymoor Consultancy).

Appendix 3 Examples of EGS development projects

Three of the most important EGS development projects, each representing a different geological setting, are described briefly below.

FENTON HILL, NEW MEXICO

The world‘s first attempt to demonstrate the feasibility of generating power from HDR began in New Mexico in the early 1970‘s, with support from the US Atomic Energy Commission. The chosen site, at Fenton Hill around 70 kilometres west of Los Alamos, sits on the western flank of the Valles Caldera (a supervolcano of around 22 km diameter) in an area associated with geologically recent volcanism and ongoing hydrothermal activity; the local geothermal gradient is approximately 65ºC/km, more than twice the global average. The HDR ‗target‘ was a large intrusion of granodiorite.

Work progressed in several phases (e.g. Brown, 1995; Duchane and Brown, 2002; Tester et al., 2006), beginning with the creation of a simple fracture system (i.e. a small HDR reservoir) between two boreholes in the depth range ~2.5 to 3.0 km (1974–79). This successfully proved the validity of the engineered reservoir concept, so work began to create a larger, deeper (~ 3.5 to 4.0 km) and more complex reservoir dominated by multiple vertical fractures. Finally, a surface plant was constructed (1987–91) and the reservoir was flow-tested (1992–95) in a manner simulating the operation of a commercial HDR facility.

The pioneering work carried out at Fenton Hills revealed, and to a large degree overcame, many of the technical obstacles associated with creating and maintaining a fit-for-purpose engineered fracture system several kilometres below ground. The key challenge lies in ensuring the fracture system satisfies several requirements simultaneously: it must have sufficient permeability to permit an adequate flow of water, and sufficient surface area to permit the required amount of heat exchange; it must connect the injection and production wells but remain effectively a closed-system (i.e. a significant amount of heated water must not ‗bleed‘ from the reservoir); and it must be stable over the projected lifetime of the EGS (probably several decades).

Important conclusions from the project included:

- hydraulic fracturing in competent crystalline rock does not create new, disc-shaped fractures (as was conceived in the original concept), but rather causes existing natural joints to open
- joints oriented roughly orthogonally to the direction of least principle stress typically open first, followed by those in other orientations as hydraulic pressure increases
- the combination of stress regime and pre-existing joint structure leads to ellipsoidal reservoirs
- a system of three wells, with an injection well in the centre and production wells at both ends, allows the highest production rate from a reservoir
- the life-span of a reservoir will be maximised by separating the wells by as great a distance as possible.

As well as proving the potential of the HDR concept, the work at Fenton Hill stimulated interest in several other countries. Germany and Japan contributed funds and personnel to the project during the 1980's, and the expertise and technology were subsequently exported to Europe and Japan.

THE EUROPEAN DEEP GEOTHERMAL ENERGY PROGRAMME

A European research programme initiated in 1987 has been developing the concept of heat and electrical power generation from a deep geothermal energy reservoir at Soultz-sous-Forêts, France, near the western border of the Rhine Graben. The consortium, made up of funding agencies (the European Commission and several French, German and Swiss government departments), and a range of industrial and scientific research partners from France, Germany and Switzerland, has effectively integrated at one site a substantial proportion of the European research activity into deep geothermal energy resources. Gérard et al. (2006) and Tester et al. (2006) have recently provided summaries of the geological setting, EGS design, and progress.

The site comprises a 1.5 km thick layer of sediments overlying three different, vertically stacked, masses of granite. The shallowest granite mass is highly fractured and hydrothermally altered in the vicinity of numerous large faults in the depth range 2.7–3.2 km. Deep hydrothermal convection cells in the fractured granite account for an abnormally high geothermal gradient of ~100ºC/km within the sedimentary rocks. Radiogenic heat supplied by the granite makes only a minor contribution to the geothermal resource in this setting.

The project at Soultz began as the European Hot Dry Rock project. However, early drilling revealed large volumes of fracture-hosted, hot saline fluid in the targeted granite reservoir rocks. The fracture system at Soultz still requires artificial stimulation to create the level of permeability required for economic heat recovery, so the project was reclassified in 2001 as an Enhanced Geothermal System (this is not currently mentioned on the project website). The concept at Soultz now involves drilling at least two boreholes into the deep fractured rock, stimulating (by hydraulic fracturing) the rock around the base of each well to enhance the permeability of the natural fracture network and connect the two wells to it, then extracting hot fluid from one well, generating power from the heat it contains, and injecting the cooled fluid back into the reservoir through the other well.

The Soultz EGS departs from the classic HDR concept in several ways. For example, the fracture network connecting the wells is part of an open system, making it more difficult to control flow rates and predict sustainability. Also, the water supplying the geothermal energy is highly saline (unlike the fresh water that is pumped through an HDR system), so the technical challenges include dealing with corrosion of metallic components in the boreholes and power generation facility, and disposing of excess saline water at the surface.

In the first ten years of the programme two boreholes were drilled (to 3.6 and 3.9 km) and stimulated, a series of geological, geophysical and hydraulic investigations was undertaken, and a long-term (4 month) circulation test was performed between the two boreholes. In a second phase of work (1997–2005) the boreholes were deepened to 5 km, where they encountered temperatures of 200 ºC, and further stimulation and circulation tests were performed. A commercial-scale EGS prototype potentially generating up to 25 MW of electrical power was developed, but this is currently struggling to generate 1 MW.

COOPER BASIN, AUSTRALIA

The recent discovery (Neumann et al., 2000) of the South Australian Heat Flow Anomaly (SAHFA), a zone of unusually high heat flow extending from Queensland to South Australia (and possibly continuing as far south as Tasmania), has sparked significant interest in geothermal energy exploration in Australia. More than a dozen companies are currently exploring tenements across an area of around 62 000 km^2, mainly in South Australia, and at least An$800 million worth of exploration and proof-of-concept investment is forecast up to 2013.

The most advanced, and probably the most exciting, prospect is in the Cooper Basin, in the north-east part of South Australia (e.g. Chopra and Wyborn, 2003). Here, gas exploration wells have penetrated granite in the basement underlying 3.5 km of late Carboniferous to Permian sediments. Samples of the granite have HP values in the range 7–10 $\mu W\ m^{-3}$, and the well data, together with seismic and gravity data, indicate that granite underlies the deepest part of the basin over an area of approximately 1,000 km^2. The top of the granite, at 3.7 km, is at approximately 240ºC, equating to an average geothermal gradient of >50ºC/km. The rock temperature is expected to increase by ~30 ºC for every additional kilometre of depth. The unusually high temperature at this relatively shallow depth is attributed to the HHP character of the granite and to its location beneath a thick layer of low conductivity sediments (including coal, which has very low thermal conductivity).

The sedimentary rocks and the granite are also currently under high geological stress, which has reduced permeability and limited the loss of heat through fluid flow. The granite pluton contains a network of fractures, dominantly in a sub-horizontal orientation, which formed when the rocks overlying it were removed by erosion, causing it to be exposed before being buried by Carboniferous sediments. These fractures are expected to make ideal pathways for circulating fluid and ideal surfaces for heat exchange, particularly following hydraulic stimulation.

Geodynamics Ltd, a private company, is leading the exploration of this potentially very significant resource. The Cooper Basin is in a remote location, and the cost of building infrastructure and transmitting power to major load centres will be considerable. Despite this, the company has been able to publish an attractive economic analysis and has raised a substantial sum of private money to prove the technical and economic viability of the resource. Geodynamics has proven the connection between two wells spaced 500 m apart, and has extracted water and steam from the production well at up to 210ºC. As of April 2009, the company had drilled its fifth deep geothermal well, completed a four-month closed loop circulation test between two of its deep wells, and built a 1MW power plant and visitor centre.

The size of Australia‘s geothermal resource potential is enormous. According to the Geodynamics company website, ―in Geodynamics tenements in the Cooper Basin a thermal resource equivalent to 50 billion barrels of oil is estimated. For comparison, Australia's current total oil reserves are 2.9 billion barrels, and the US oil reserves are 20 billion barrels”. Identified HHP granites in Australia have the potential to meet the total electricity demand of the country for hundreds of years.

The ‗buried hot granite‘ setting that is being exploited in the Cooper Basin has a significant advantage over the ‗classic‘ HDR concept illustrated in Figure 1: instead of rising to the surface and being lost to the atmosphere, much of the radiogenic heat generated by the granite over many millions of years is trapped beneath the overlying low conductivity rocks, which act like a thermal blanket. Compared to sites where HHP granite crops out at the surface, ‗buried hot granite‘ settings theoretically allow larger heat reservoirs to develop at the same or shallower depths, from rocks of similar or lower HP capacity.

Glossary

Andesite	A type of volcanic igneous rock that has small crystals and moderate silica content, and typically forms sheet-like intrusions (dykes and sills) or lava flows.
Archaean	A span of geological time between 4,000 and 2,500 million years ago, representing a large part of Earth‘s early history.
Basalt	A type of volcanic igneous rock that has small crystals and low silica content, and typically forms sheet-like intrusions (dykes and sills) or lava flows.
Basaltic-rock	A general term referring to basalt and similar rocks.
Batholith	A group of more-or-less contiguous intrusions that collectively form a continuous or near-continuous mass that is significantly larger than a typical individual pluton.
Buried hot granite	A geological setting relevant to deep geothermal energy assessments, in which an intrusion of granite, ideally with High Heat Production (HHP) character, occurs beneath a moderately thick (ideally 2-5 km) cover of low thermal conductivity rocks (e.g. sedimentary rocks or low-silica igneous rocks).
Caledonian Orogeny	Collective term for the structural and thermal geological events arising from closure of the Iapetus Ocean and associated collision of continents between approximately 500 and 400 million years ago.
Carboniferous Period	A span of geological time between 359 and 299 million years ago.
Crust	Earth‘s outermost layer, comprising a thin ‗skin‘ of relatively cool and brittle rocks sitting directly on the mantle.
Devonian Period	A span of geological time between 416 and 359 million years ago.
Diorite	A type of igneous rock that has relatively large crystals and moderate silica content, and typically forms intrusions.
Fault	A type of fracture formed when a rock mass breaks under strain and the opposing sides of the break move relative to each other and parallel to the fracture. Earthquakes occur when faults form or move.
Fracture	A physical break in a rock mass.
Geothermal gradient	The rate at which temperature increases with depth in the crust.

Gabbro	A type of igneous rock that has relatively large crystals and low silica content, and typically forms intrusions.
Granite	A type of igneous rock that has relatively large crystals and high silica content, and typically forms intrusions.
Granitic-rock	A general term referring to granite and similar rocks (mainly granodiorite and tonalite).
Granodiorite	A type of igneous rock that has relatively large crystals and high silica content, and typically forms intrusions. Granodiorite is usually less chemically evolved than granite.
Heat flow	The movement (or transfer) of heat through the Earth. Also the standard measure of the amount of heat travelling through Earth's crust (heat flow = thermal conductivity x geothermal gradient).
Heat production (HP) capacity	The quantity of heat that can be produced by a rock through in situ decay of radioactive elements.
High heat production (HHP) granite	Granite that has an unusually high heat production (HP) capacity. Also, the intrusion (or pluton) formed of such rock.
Joint	A type of fracture formed by simple opening in a rock mass (i.e. a crack).
Mantle	The zone of the Earth immediately beneath the crust and overlying the core.
Neoproterozoic	A span of geological time between 1,000 and 542 million years ago.
Ordovician Period	A span of geological time between 488 and 443 million years ago.
Pluton	An intrusion of granite larger than approximately one kilometre in diameter at outcrop.
Palaeozoic	A span of geological time between 542 and 251 million years ago.
Peridotite	A type of igneous rock that has relatively large crystals and very low silica content, and typically forms intrusions.
Permian	A span of geological time between 299 and 251 million years ago.
Permo-Triassic	A span of geological time encompassing both the Permian and Triassic periods, between 299 and 199 million years ago.
Proterozoic	A span of geological time between 2,500 and 542 million years ago.
Pyroclastic rock	A type of igneous rock formed by explosive eruption and consisting of an accumulation of rock fragments.

Radiogenic	Produced by a process of radioactive decay.
Shale	A type of sedimentary rock formed of very fine-grained particles, which can be easily split along closely spaced planes.
Silurian	A span of geological time between 443 and 416 million years ago.
Syenite	A type of igneous rock that has relatively large crystals and moderate silica content, and typically forms intrusions.
Tectonic plate	A rigid, thin segment of Earth's crust and upper mantle which moves horizontally and adjoins other plates along zones of seismic (earthquake) activity.
Tertiary	A span of geological time between 65 and 2.5 million years ago. Also known as the Cenozoic Era.
Thermal conductivity	A measure of the ability of a material to conduct heat.
Tonalite	A type of igneous rock that has relatively large crystals and high silica content, and typically forms intrusions. Tonalite is usually less chemically evolved than granite.
Triassic	A span of geological time between 251 and 199 million years ago.
Volcaniclastic rock	A type of igneous or sedimentary rock formed of fragments of igneous rock.
Wacke	A type of sandstone in which the detrital grains are poorly sorted (i.e. there is a wide range of grain-sizes). Wackes typically have low proportions of pore space and low permeability compared to well-sorted sandstones.

Abbreviations

$\mu W\ m^{-3}$ = microwatts per cubic metre

$g\ cm^{-3}$ = grams per cubic centimetre

$mg\ kg^{-1}$ = milligrams per kilogram (equivalent to ppm)

ppm = parts per million

$kg\ m^{-3}$ = kilograms per cubic metre

HP = heat production

HHP = high heat production

$mW\ m^{-2}$ = milliwatts per metre square

ºC/km = degrees Celsius per kilometre

$W\ m^{-1}\ K^{-1}$ = watts per metre per degree Kelvin (one degree Kelvin = one degree Celsius)

EGS = Enhanced (or Engineered) Geothermal System

µW = microwatt

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