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Geothermal Prospects in the United Kingdom

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ABSTRACT

Geothermal energy development in the UK has been limited, partly due to the lack of high enthalpy resources, but also due to the availability of cheap fossil fuels during the 1980s and 1990s. However, with the advent of renewable energy sources to combat climate change and the need to replace diminishing fossil fuels, geothermal is now in a good position to contribute to the energy mix. In this paper, some of the geothermal prospects are reviewed and some recent work from the British Geological Survey in the following areas is presented:

- The potential of combined heat and groundwater flow modeling and the latest three-dimensional geological models are being assessed for use in ground source heat pump prospecting.
- Temperatures in the shallow sub-surface have been collated and compared to modeled results in order to identify thermal anomalies that would be advantageous for direct use applications or ground source heat pumps.
- There is renewed interest in EGS within the granite batholith of southwestern England, and a reappraisal of the Hot Dry Rock potential of the Scottish granites suggests that this resource may have been underestimated.

1. INTRODUCTION

The United Kingdom is situated on the stable foreland of Europe and is devoid of active volcanism and high heat flows that result from tectonic activity. This at least partially explains why geothermal energy plays a very small role in the UK. It was estimated in 2006 that all renewables only contributed 1.5% of the UK's energy mix (DBERR, 2008), and geothermal only contributed a fraction of this. However, when comparisons are made to countries in a similar tectonic setting, it is clear that the UK is underutilizing this potential resource. In 2005, Sweden was reported to have 3840 MWt of installed direct use geothermal capacity (Lund et al., 2005). The lack of geothermal development has largely been a result of the availability of North Sea natural gas that provided a cheap and secure energy supply throughout the 1980s and 1990s. However, with the passing of peak hydrocarbon production in the North Sea and new renewable energy targets (15% by 2020; DBERR, 2008), geothermal resources are being reappraised. In this paper, previous assessments of the UK's geothermal resources are reviewed, and future prospects are discussed.

2. THE GEOTHERMAL ENERGY PROGRAM

The geothermal potential of the UK was investigated by a program funded by the UK government and the European Commission that ran from 1977-1994. It comprised three elements: an appraisal of heat flow, an investigation of the potential of hot brines in deep sedimentary aquifers that might be suitable for electricity generation or direct use applications, and an investigation of radiothermal granites that might be exploited as Hot Dry Rock (HDR) reservoirs. The results have been summarized in Downing and Gray (1986a, b), BGS (1988), Parker (1989, 1999) and Barker et al. (2000).

The heat flow map of the UK is shown in Figure 1 (Lee *et al*., 1987; Downing and Gray, 1986a, b; Rollin, 1995; Rollin *et al*., 1995; Barker *et al*., 2000). It comprises 212 heat flow measurements augmented by 504 heat flow estimates. There is a fairly uniform background field of around 52 mW m^{-2}. Areas of increased heat flow are associated with the radiogenic granites in southwestern England (mean value of 117 mW m^{-2}) and the buried granites of northern England. Values are also above the regional background over the batholith in the Eastern Highlands of Scotland. The average UK geothermal gradient is 26 °C km^{-1}, but locally it can exceed 35 °C km^{-1}.

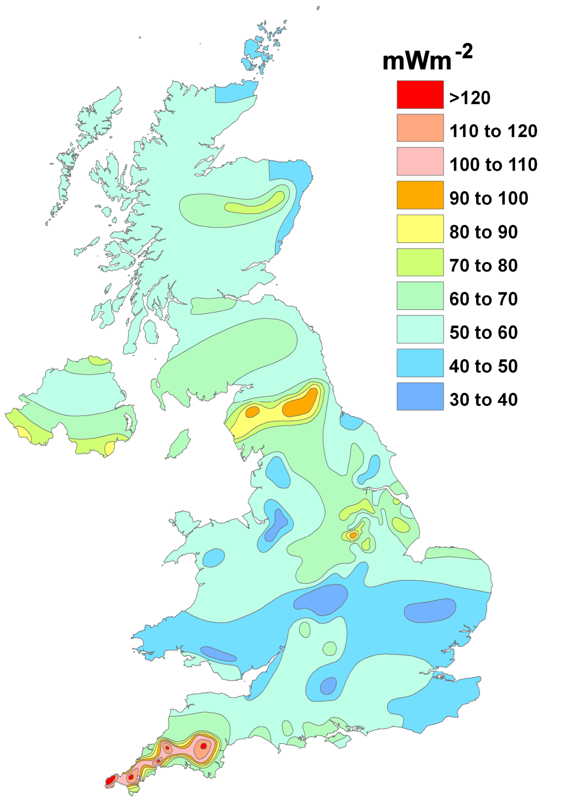

Figure 1. Heat flow map of the UK.

Temperature measurements were published in a geothermal catalogue (Rollin, 1987). It contains 3057 subsurface temperatures from 1216 sites, 567 of which are from wells with depths greater than 1 km. The catalogue also contains 4694 thermal conductivity measurements of core samples and formation chippings from 113 sites. Estimations of temperatures with depth were made from the heat flow values combined with a generalized thermal conductivity section that was based on a generalized vertical geological section. The estimated temperatures at a depth of 7 km are shown in Figure 2 (Downing and Gray 1986a; Barker et al., 2000). Temperatures could be as high as 260 °C within the granites of southwestern England and 240 °C within the buried granites of northern England, but temperatures rarely exceed 140 °C elsewhere.

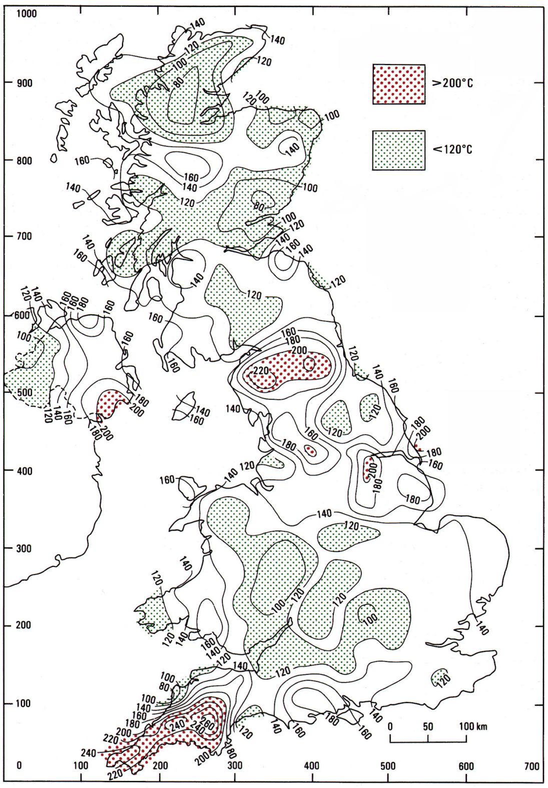

Figure 2. Estimated temperatures at a depth of 7 km. Contours are in ºC. (After Downing and Gray, 1986a).

Within the UK the only sedimentary aquifers that lie at sufficient depths and have suitable hydrogeological properties for low enthalpy geothermal applications (i.e. temperatures > 40 °C) are the Permo-Triassic sandstones. These are found in four deep sedimentary basins in England and Wales (shown in Figure 3) and two in Northern Ireland. Temperatures within the sandstones are generally 40-60 °C with a maximum of 100 °C occurring within the Cheshire Basin, where Permian sandstones are found at depths greater than 3.5 km, as shown in Figure 3. Permeabilities range from 150 mD to 5 D and transmissivities range from 10-80 Dm. The geothermal resource (i.e. the total heat in place for the Permo-Triassic sandstones aquifers) was estimated to be $327x10^{18}$ J (Rollin et al., 1995).

During the program, four geothermal exploration wells were drilled in Southampton, Marchwood, Cleethorpes (shown in Figure 3) and Larne (Northern Ireland). The well in Southampton was developed by a partnership between Southampton City Council and a private company to become the only deep commercial geothermal project in the UK. Brine from a depth of 1.8 km at 76 ºC rises naturally to within 100 m of the surface. At a surface temperature of 74 ºC, it is then pumped to a heat exchanger, where the heat is transferred to clean water. The brine is then discharged to the sea at 28 ºC. The heated water supplements a combined heat and power generator and is used in a district heating scheme within the city centre.

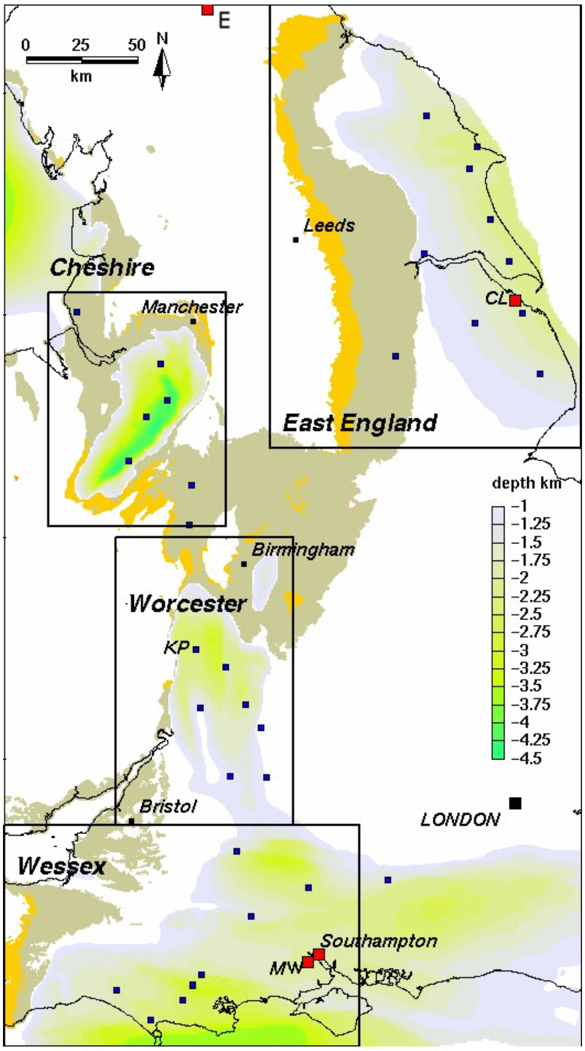

Figure 3. Deep sedimentary basins in England and Wales comprising the East England, Cheshire, Worcester and Wessex Basins. Depths are colour coded in km. Light brown shading corresponds to the outcrop of Permian and Triassic sandstone and mudstone; yellow shading is Lower Permian strata. Geothermal boreholes are indicated by red squares; Southampton; MW – Marchwood; CL – Cleethorpes; E – Eastgate.

The Hot Dry Rock (HDR) experiment was conducted in the Carnmenellis granite in southwestern England, where heat flows are around 120 mW m^{-2} and there is a constant geothermal gradient of 35 ºC km^{-1}, as shown in Figure 1. The project, which was never intended to produce electricity, was a rock mechanics experiment to research the hydraulic stimulation of fracture networks at temperatures below 100 ºC. Three wells were drilled to a total vertical depth of 2.6 km where the bottom-hole temperature was around 100 ºC. A reservoir was created by hydraulic stimulation followed by a series of circulation tests. One of the main findings of the HDR project was that hydraulic fracturing stimulates natural fractures by shearing, which are then self-propping on the naturally rough surfaces and stay open rather than creating new fractures by tensile fracturing (MIT, 2006). In 1994, the HDR project was closed, and research effort was transferred to the European Geothermal Project at Soultz-sous-Forêts.

3. RECENT GEOTHERMAL DEVELOPMENTS

The Geothermal Energy Program demonstrated that temperatures > 150 ºC are only found at great depths and that conventional geothermal generation of electricity (within the depth range of 2-3 km) is not possible in the UK. The only tangible legacy of the program was the Southampton geothermal energy scheme. Research on the utilization of the UK's geothermal energy resources dwindled to a very low level during the late 1980s and 1990s. The introduction of ground source heat pumps (GSHP) was very slow there. Whilst some European countries reported the installation of several thousand per year, in the UK it was on the order of tens per year (Curtis, 2001; Sanner et al., 2003). The reasons for this included the resistance of well established energy markets, little training for the installation of GSHP systems, lack of design software (BRE, 2004) and the complexity of the geology in the UK (Curtis, 2001).

In 2004, the first deep geothermal exploration borehole to be drilled in the UK for over 20 years was drilled at Eastgate (shown in Figure 3) into the Devonian, Weardale granite (Manning et al., 2007). The borehole was drilled to take advantage of the high geothermal gradient associated with the radiothermal granite, not as a HDR or EGS (Engineered Geothermal System) resource, but for direct heat use applications. The borehole was targeted to intersect the fractured hydrothermal system associated with a deep mineralized vein called the Slitt Vein. The borehole was drilled to a total depth of 995 m, 723.5 m of which was within the granite. A bottom hole temperature of 46 ºC was encountered within the granite and the natural fracture network was found to be highly permeable (transmissivity c. 2000 Dm). Water yields have been estimated at up to 1600 m^3 day^{-1} (Manning et al., 2009). Hence, the Eastgate borehole is considered to have significant exploitation potential for direct heat use (Manning et al., 2007).

4. FUTURE GEOTHERMAL PROSPECTS

4.1 Ground source heat pumps

The number of ground source heat pumps is increasing and will continue to increase. In 2006, the Ground Source Heat Pump Association was formed to represent the industry. It promotes best practice, disseminates industry approved technical standards, and represents the industry to other bodies including government. The total number of new installations per year is difficult to estimate, as there is no central regulatory authority for closed loop systems (although open loop installations require water extraction and discharge licenses). In central London, open loop ground source heat pump systems are being installed within the underlying chalk aquifer for cooling. It is reported that there are 11 active schemes with an additional 68 proposed (Fry, 2007). Since these installations return the heated water back to the aquifer, it is clear that there is a limit to the total number of installations before there is a danger of thermal breakthrough between the schemes. Increasingly sophisticated groundwater and thermal modeling is required in the planning and design of new schemes (Gropius and Etheridge, 2007; Herbert et al., 2007). Ultimately, if balanced thermal loads cannot be achieved during an annual cycle, surplus heat stored in the aquifer system will need to be rejected using cooling towers.

Thermal modeling of closed loop systems can be used to create regional prospecting maps for ground source heat pumps that can aid in the early design phase. Modeling is also important in the assessment of abandoned mine workings that are flooded and can be utilized as a thermal resource (Banks et al., 2003). A study spanning England and Wales (Wiltshire and Burzynski, 2008) identified some 320-340 abandoned coal mines where there was sufficient information to estimate the resources. The potential geothermal capacity was estimated to be 1983 MWt. Many abandoned mine working are located in close proximity to urban centers and represent a significant potential resource. The BGS have created modern 3D digital geological models that are being utilized for combined water flow and thermal modeling in urban areas underlain by abandoned mine workings. These should enable an accurate assessment of the thermal resource and help to indicate how it might be exploited.

4.2 The shallow temperature field

Shallow sub-surface temperatures are one of the key parameters required when assessing the potential for a ground source heat pump or a shallow direct heat use application. Regions with high temperatures have the most potential. It is possible to consider a stable background temperature field determined by an upper boundary representing the ground surface, resulting in a temperature that is equal to the mean annual air temperature at a depth of 10 – 15 m (Rybach & Sanner, 2000). This temperature increases with depth according to the geothermal gradient, which is determined by the vertical heat flow and the thermal conductivity of the rocks. Hence, if the geological succession is known, it is theoretically possible to estimate the temperature at any depth.

In practice, observed temperatures differ from estimated temperatures for a variety of reasons.

- Heat flow is not one dimensional and is also affected by lateral variations in thermal conductivity, a phenomenon often referred to as heat refraction.

- Ground water flow transports heat by advection, and there is convection within any permeable horizon. Such mechanisms could create both high and low temperature anomalies. The most obvious examples of this in the UK are the thermal springs at Bath (Gallois, 2007) and in the Peak District (Brassington, 2007), where ground water is able to rise relatively rapidly through fractured Carboniferous Limestone.

- Internal heat production from natural radioactive decay within buried granites increases heat flow. This also increases temperatures in the overlying sedimentary rocks, especially where they have lower thermal conductivities. Heat flow measurements taken above buried granites should include an element for the extra heat production, but heat flow boreholes are sporadically located. Thus, it is possible that buried heat production sources have not been accounted for.

Boreholes with geological logs have led to generic thermal conductivities being assigned to each of the geological layers. In order to identify temperature anomalies, temperature estimates were made for the East Midlands of England at a depth of 200 m using Fourier's Law of heat conduction:

$$q = -\lambda \text{ grad } T$$

where q = heat flow (W m^{-2}), λ = thermal conductivity (W m^{-1} K^{-1}) and grad T = temperature gradient (K m^{-1}). The resulting estimated temperature map is shown in Figure 4a. This can be compared to the map shown in Figure 4b, which was constructed from actual temperature measurements at a depth of 200 m. The temperature measurements are derived from a number of sources including bottom hole temperatures, logs and coal field measurements. Some are equilibrium measurements while others will were taken after only a short interval after the cessation of circulation of drilling mud. Since the effect of drilling mud is to depress temperatures, any errors arising from non-equilibrium data are expected to produce reduced temperatures. The main trend in these two plots is the same with temperatures increasing by a few degrees in the eastern part of the region. The main difference occurs due to the three measured values exceeding 22 ºC. The implied positive temperature anomalies should not be related to non-equilibrium measurements, but could have arisen from errors such as poorly calibrated equipment. The paucity of data is the main drawback for this type of analysis, but work to obtain reliable temperature data for many regions in the UK at a number of different depth intervals is continuing.

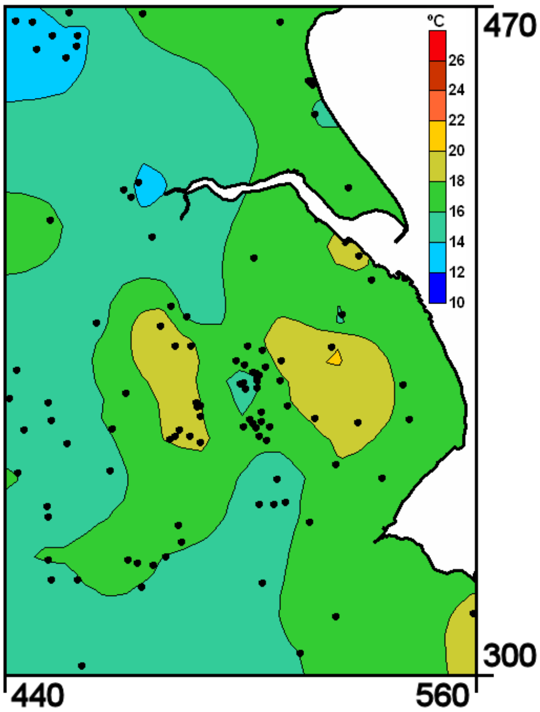

Figure 4a. Estimated temperatures at a depth of 200 m for the East Midlands of England. Black dots indicate the locations of boreholes used in the map.

4.3 Engineered geothermal systems

As in many other parts of the world, there is renewed interest in Engineered Geothermal Systems (EGS). There are even current proposals to create a commercial EGS project within the granitic rocks of the southwestern England (Baria, 2009). The intrusions of the East Grampians batholith of Scotland (shown in Figure 5) were considered during the Geothermal Energy Program. Four intrusions (Cairngorm, Mt Battock, Ballater and Bennachie) were drilled to 300 m depths and heat flow and heat production values were measured. Compared to other UK granites, the East Grampians intrusions have the highest heat production values (5.0-7.3 μW m^{-3}), but the heat flow values are only moderately elevated (~30% higher, in the range 59-76 mW m^{-2}) with respect to the average value for the UK. Gravity evidence indicates that the granite extends to 13 km depths. Thus, the association of promisingly high heat production values and surprisingly low heat flow values was interpreted to reflect two factors: (i) much more rapid decrease in heat production with depth than that occurring in other intrusions, and (ii) relatively low background heat flow in the region.

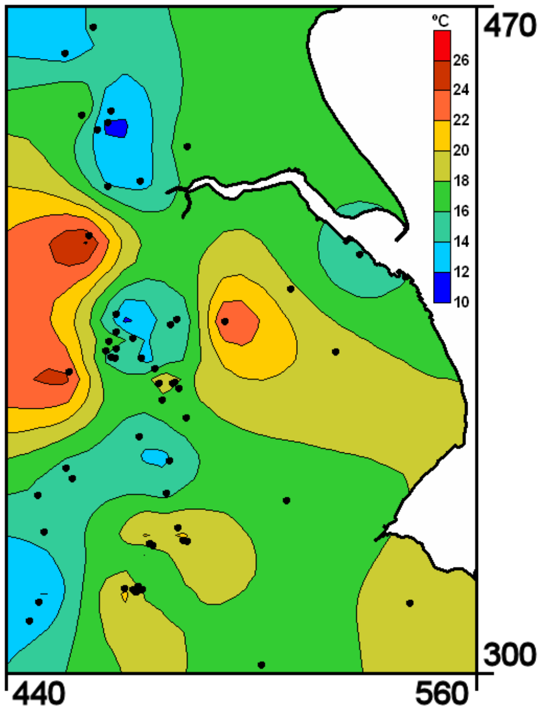

Figure 4b. Measured temperatures at a depth of 200 m for the East Midlands of England. Temperatures are derived from bottom hole measurements, logs and coal field measurements. Black dots indicate the locations of boreholes used in the map.

The implied strong vertical fractionation of radiothermal elements has been researched by resurveying since the mid 1980's (British Geological Survey 1989; 1992; 1993a,b; 1995a,b,c; 1996a,b; Harrison, 1987; Thomas et al., 2004). The intrusions are now recognized to have a complicated multi-phase emplacement history. The presently exposed surface of each intrusion probably lies less than 2 km below the former plutonic roof, in a zone situated at the top of an evolving magma system. Within this zone, multiple batches of highly fractured radiothermal granite magma were emplaced in rapid succession. Much of the magma fracturing may have occurred prior to emplacement at deeper levels in the system, and there was probably little additional fracturing following emplacement. Therefore, the radiothermal elements may not be vertically fractured within the exposed outcrop zone, and this zone is likely to be of limited vertical extent, perhaps 1-2 km. Some other Scottish granite outcroppings are thought to be related to the East Grampians batholith, but the exposure may represent deeper levels. The heat production values for

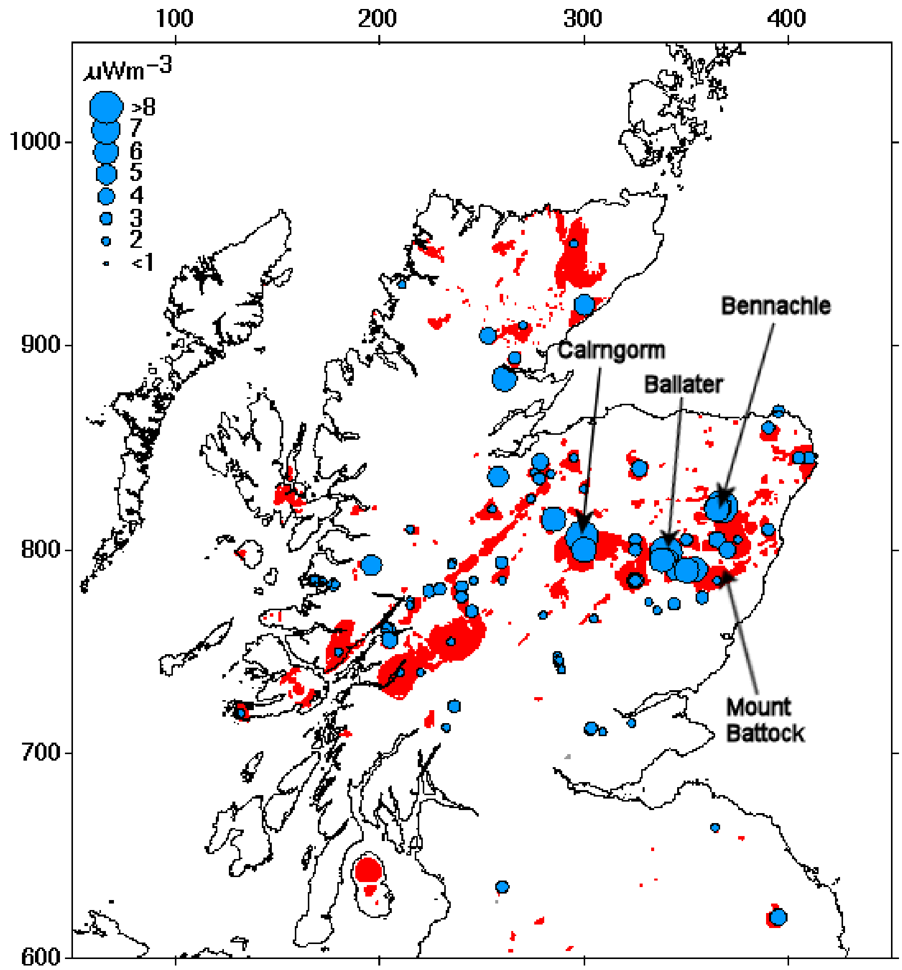

Figure 5. Outcropping granite intrusions, shown in red, for Scotland. Intrusions of the East Grampians batholith considered during the Geothermal Energy Program are labelled. Heat production values are indicated by the blue circles.

these plutons range from 2.6-4.9 μW m^{-3}, which is less than that in the East Grampians, but comparable to those in other UK granites, including those in southwestern England. Hence, with heat production values in this range over a significant vertical extent below the 1-2 km roof zone, actual heat flow values would be expected to be higher than the measured values.

The heat flow measurements were made in 300 m deep boreholes within the depth range of climate-induced transient changes to the geothermal gradient. The amplitude of post-glacial warming has been generally accepted to be quite small and so a climate correction was not applied to the heat flow measurements (Downing and Gray, 1986a). More recently, it has been argued that warming at the end of the last glaciation was significantly greater than previously thought and that heat flow values determined from boreholes less than 2 km deep could be underestimated by up to 60% (Gosnold et al., 2005). If this theory is correct, climate-induced transient changes to the near-surface geothermal gradient may partially explain why heat flow in the East Grampians granites (which crop out well to the north of the southern limit of glaciation in Britain) is significantly lower than heat flow in the granites of south-west England (which crop out south of the glacial limit). If this is shown to be a significant factor, it will increase the prospects of developing EGS in Scotland.

5. CONCLUSIONS

The focus of the Geothermal Energy Program of the 1970s and 1980s was to appraise the UK's geothermal potential for electricity generation. Since the UK is not endowed with high geothermal gradients and HDR technology was in its infancy at that time, many considered this program to have failed. As a result, there has been little investment in geothermal research or in further appraisals of potential resources. However, the energy landscape has now changed due to rising energy prices, concerns about the security of energy supplies, and renewable energy targets. Renewable heat from geothermal sources can contribute significantly toward meeting the UK's renewable obligations. Ground source heat pumps and direct heat use applications are on the rise. Shallow temperature data is available for some regions, but this needs to be more widely collated and appraised in order to provide reliable resource maps. Modeling is also important in planning the exploitation of shallow resources, especially as the number of geothermal projects increases and as the potential of flooded mine workings is more widely considered. Heat is not licensed or regulated (except as a pollutant) in the UK, but this may need to change if thermal interference between projects becomes a problem. Electricity generation from Engineered Geothermal Systems is now in the planning stages in southwestern England. A reappraisal of the East Grampians granite batholith in Scotland suggests that this may have more potential than was originally thought. The largest volumes of granite in the UK are found in Scotland. Higher temperatures and EGS applications are possible where intrusive granites are blanketed by low conductivity sedimentary rocks.

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