Proc. 8th NZ Geothermal Workshop 1986

THE GEOTHERMAL POTENTIAL OF THE UNITED KINGDOM

D J ALLEN

BRITISH GEOLOGICAL SURVEY
WALLINGFORD, OXFORDSHIRE U.K.

ABSTRACT

The United Kingdom forms part of the stable continental foreland of north-west Europe. The average background surface heat flow is 52 mW/m² but there are several anomalies with values ranging up to 136 mW/m² superimposed on the background field. Three of these are associated with granite batholiths in Cornwall. northern England and the Eastern Highlands of Scotland.

Two potential sources of geothermal energy have been investigated in the UK: the Hot Dry Rock resource, which depends on the heat stored in impermeable rocks at depths greater than 3 to 4 km: and the low enthalpy resource provided by aquifers in sedimentary basins at depths up to about 3 km.

The granite batholith of Cornwall has been extensively investigated as an HDR target. Several exploration wells have been drilled with depths up to 2.5 km, with bottom hole temperatures of about 80 C. A temperature of 200 C would be expected at about 5.4 km.

The low enthalpy geothermal potential of the Permo-Triassic sandstones present in several sedimentary basins has been investigated and significant resources have been identified at temperatures up to about 85 C. Three geothermal exploration wells and one development well have been drilled.

The Accessible Resource Base (ARB) to a depth of 7 km is 2.75 x 10^{23} joules, and the Hot Dry Rock ARB at temperatures of more than 100 C and at depths of less than 7 km is 36 x 10^{21} joules. The low enthalpy identified resources of the Permo-Triassic sandstones at temperatures above 40 C amount to 5.2 x 10^{19} joules.

The extent to which the geothermal resources of the UK could be used depends on the successful implementation of the HDR concept, the development of suitable cheap heat pumps. and the cost of the energy in relation to other fuels.

INTRODUCTION

The marked increase in energy prices in the mid-1970s led to greater world-wide interest in less conventional forms of energy, including geothermal energy. In the United Kingdom, initial studies of the feasibility of developing geothermal energy were encouraging and, as a consequence, the Department of Energy decided to support a more detailed study of its possible potential. The programme also received financial support from the Commission of the European Communities.

The UK is not an area that is immediately associated with geothermal energy. It is part of the stable foreland of north-west Europe an2 is remote from plate margins. The last major episode of volcanic activity occurred during Tertiary time and the igneous intrusions which were formed then have long since cooled to equilibrium temperatures. The average heat flow is near to the world mean and suface geothermal manifestations are limited to a few thermal springs. the hottest of which is 47 C at Bath.

In view of the lack of natural high-enthalpy geothermal fields in the UK, geothermal research has been undertaken in two directions: the exploration of the Hot Dry Rock (HDR) concept in granite batholiths, and the assessment of low-enthalpy resources in the form of deeply-buried aquifers in sedimentary basins.

Geothermal research in the UK has been carried out primarily by the British Geological Survey, the Camborne School of Mines, and several university departments.

HEAT FLOW

In the UK the geothermal gradient in the upper few kilometres of the crust ranges from about 15 to 40 C/km, with an average measured value of 26 C/km (Wheildon and Rollin 1986). The true average value is.. likely to be less than this - of the order of *20* Cfkm - because measurements have been biased to sedimentary basins, which are often areas of low thermal conductivity and therefore of higher gradient.

Heat flow in the UK is considered to be mainly conductive and the basic equation used to assess one-dimensional (vertical) heat flow is the Poisson equation

$$\frac{d}{dz}\left(\lambda \frac{d\theta}{dz}\right) = -A \qquad 1$$

where z is depth, λ is thermal conductivity, θ is temperature and A is heat production.

The prediction of sub-surface temperatures therefore requires the integration of this equation with various assumptions about the vertical distribution of thermal conductivity and heat production. For sedimentary rocks the heat production term is assumed to be negligible. and if the temperature dependence of thermal conductivity can be ignored then equation 1 can be integrated to yield

$$\theta_z = \theta_g + q \sum_{i=1}^{n} \frac{t_i}{\lambda_i} \qquad 2$$

where θ_z is the temperature at depth z, θ_g is the surface temperature, λ_i is the thermal conductivity of layer i. q is the background heat flow and t is the thickness of layer i.

The equation assumes a horizontally layered crust with n layers to a depth z and is used to predict sub-surface temperatures in areas of negligible heat production. It is also used to calculate surface heat flows from temperature and thermal conductivity measurements in all areas, as it is assumed that the heat production over the depth of a borehole even in an area of high heat production will be negligible

Heat flow calculations in the UK have been based on the solution of equation 2 by measuring the geothermal gradient in boreholes and by determining the thermal conductivity of the corresponding rock type from rock samples.

In 1975 there were only 32 values of surface heat flow in the UK. Since then the number for sedimentary sequences and granites has increased to 188. Heat flow values have been obtained from a variety of sources including hydrocarbon exploration wells, stratigraphical test boreholes and geothermal exploration wells. The most reliable calculations however have been based on measurements in purpose-drilled heat flow boreholes which are typically 300 m deep and cement-lined. In addition, values have been estimated at sites where temperature measurements are available and where the geological seqence is also known. Heat flows were estimated from equation 2 by allocating the appropriate thermal conductivity value to the various formations in the sequence, using a data file of mean thermal conductivities for the principal formations in the UK. The 188 observed values of heat flow together with the most reliable estimates (about 100 values) have been used to produce a heat flow map (Figure 1) and all values are listed in the Catalogue of geothermal data for the land area of the UK (Burley and others. 1984).

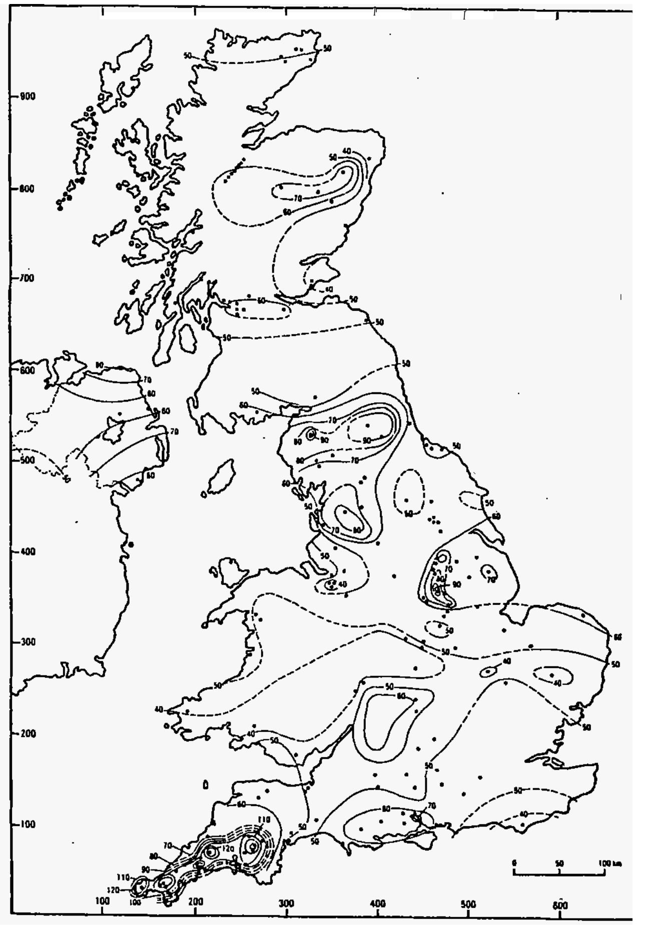

Figure 1. Heat flow map of the UK. Units are mW/m^2. Sites where heat flow has been observed are indicated. (From Wheildon and Rollin, 1986).

The heat flow data for the map are based on several assumptions which have an important bearing on its interpretation. Firstly it is asssumed that heat flow is conductive only. In fact even very snall flows of groundwater can transfer significant quantities of heat (see for example Eappelmeyer, 1979) and such convective effects can be important in all rocks - even in crystalline material (Drury. 1984). In the UK, while conduction is probably the most important heat transfer mechanism, the heat flow observations made in sedimentary basins should be regarded only as apparent conductive heat flows (Gale and Downing, 1986).

Another assumption on which the heat flow equations are based is that flow is one-dimensional. directed vertically. However lateral variations in thermal conductivity and in heat production will result in horizontal components of heat flow. These are important when considering in detail the anomalies at possible HDR sites.

Sub-surface temperatures in the UK have been affected by Pleistocene glaciations. Most of the heat flow data on which the map is based are not corrected for this effect because of uncertainties in the type of correction necessary. This is not important for compnrative regional studies but it leads to a slight underestimate of heat flow nnd therefore of predicted temperatures at depth.

The values from which the heat flow map is constructed range from 17 to 136 mW/m^2 (British Geological Survey, 1985). In general the pattern is of a background heat flow with an area-weighted mean of 52 ± 9 mW/m^2 superimposed on which are several local anomalies.

The three most extensive anomalies are associated with granites with high values of heat production (Figures 1 and 2). These are: the south-west England Hercynian batholith, with a maximum heat flow value of 136 mW/m^2 and with surface heat-production values in the range 4.0-5.3 $\mu W/m^3$: the Lake District and Ueardale Caledonian granites in northern England with a maximum heat flow value of 101 mW/m^2 ond with surface heat production in the range 3.3-5.2 $\mu W/m^3$; and finally the Caledonian batholith below the Eastern Highlands of Scotland with a maximum heat flow value of 76 mW/m^2 and with surface heat production in the range 4.8-7.3 $\mu W/m^3$.

Of the remaining features the most important is that centred on east Nottinghanshire in central/eastern England. There is evidence that this is caused by convective heat flow as a result of groundwater movement from the Pennine outcrop of Carboniferous strata. The other minor anomalies are as yet unexplained. For example the small positive anomaly in the Wessex Basin in southern England may be due to groundwater circulation. Alternatively it may be caused by a buried granite (for which there is some evidence based on gravity data).

The presence of anomalously high values of heat flow over granitic rocks with high values of heat production suggests HDR as a potential source of geothermal energy in the UK. Also, in areas where average or above average values of heat flow occur through deeply-buried aquifers. low enthalpy resources may be available. particularly in areas where sediments with low thermal conductivities increase the geothermal gradient.

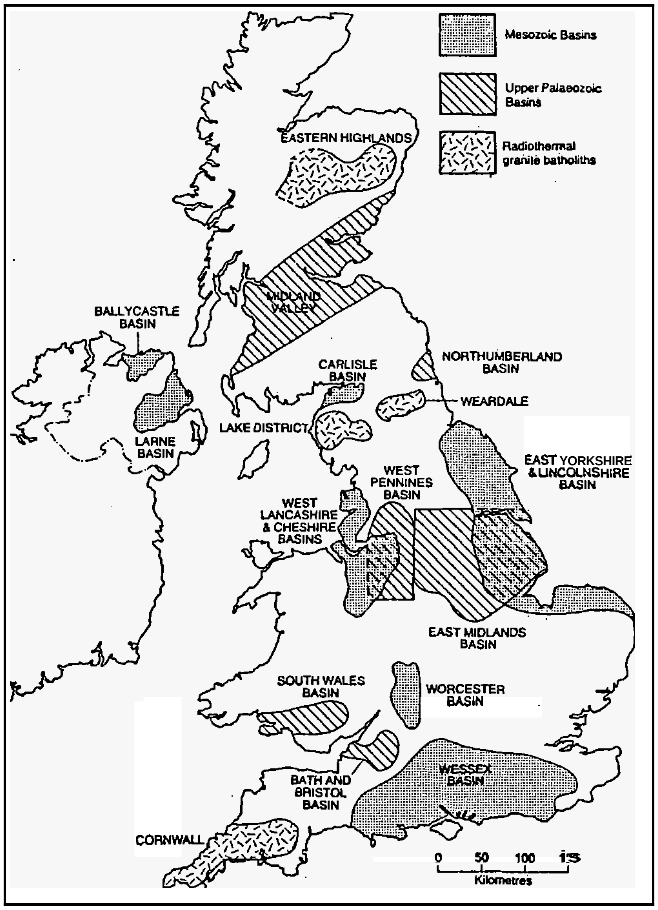

Figure 2. Principal Mesozoic and Upper Palaeozoic sedimentary. basins and radiothermal granites in the UK. (From British Geological Survey, 1985).

HOT DRY ROCK

The possibility of extracting geothermal energy from rocks of low permeability at high temperatures is generally referred to as the Hot Dry Rock concept and has been described by numerous authors (e.g. Smith, 1975, Batchelor, 1982). The technique usually proposed is to create a region of fractured rock at depth between two boreholes. either by the stimulation of naturally occurring joints or by creating artificial fractures. Cold water is pumped down the injection borehole and passes through the fractured region, which acts as a heat exchanger: hot water or steam is recovered from the production borehole. Heat is extracted from the produced fluids with a heat exchanger at the surface.

The target temperature of an HDR system depends on the end use of the extracted heat. Most applications envisage temperatures above 150 C - and usually above 200 C for electricity generation - but lower temperatures may be acceptable for other applications.

In the UK the most promising areas for applying the HDR concept are in the regions of elevated heat flow associated with granitic intrusions. These granites are characterised by the presence of the heat-producing radioactive elements uranium, thorium and potassium which result in a high heat production. The gronites also produce large negative gravity anomalies, indicating large intrusive volumes extending to significant depths.

The prediction of sub-surface temperatures in granitic rocks requires a model for the variation of heat production with depth in order to solve Equation 1. Various models have been proposed to explain the vertical distribution of heat producing elements and the observation that the surface heat flow varies with surface heat production. In the UK an exponential function has been used, although calculations have shown that down to 7 km the calculated temperature is relatively insensitive to the type of heat distribution function employed (Wheildon and Rollin, 1986). Of more importance is the accurate observation of heat flow. and reliable thermal conductivitv and heat production data.

Detailed studies have been carried out on several granite intrusions to measure heat flow and heat production, to study geochemical variations and the distribution of radioactive elements, and to interpret the sub-surface shape of the intrusions from gravity data. in order to assess their HDR potential. The best HDR prospect and the most extensively explored is the Cornubian batholith in Cornwall.

Cornubian batholith

The Cornubian batholith is about 200km long. 20-30 km wide and 10-20 km deep.' It is exposed in five main outcrops in south-west England and in the Scilly Isles. As noted above, both heat flow and heat production values associated with the batholith are high. heat flows exceeding 110 mW/m^2 over much of the outcrop. The general uniformity of heat flow values over the intrusion and the coincidence of the heat flow 'anomaly with the batholith's position suggests little lateral transfer of heat by convection (Lee. 1986). Predicted sub-surface temperatures for the Carnmenellis granite in the Cornubian batholith are shown in Figure 3. The profile predicts a temperature of 80 C at 2 km - a value subsequently verified by drilling (Batchelor. 1985) . and *200* C at 5.4 km.

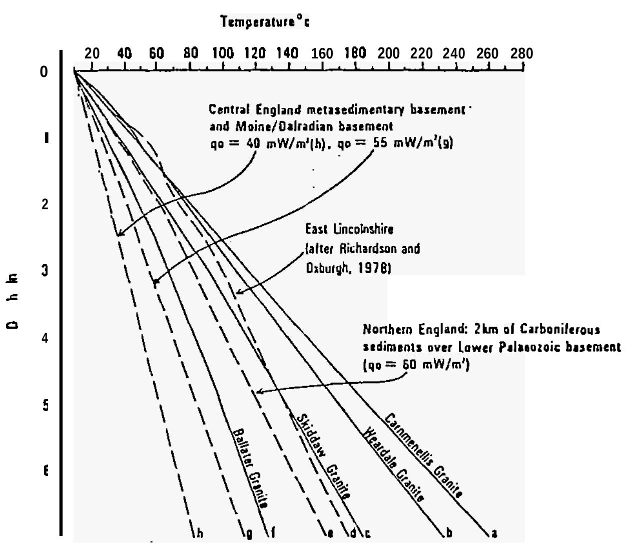

Figure 3. Comparison of predicted sub-surface temperature profiles for British granites and basement rocks. (From Lee, 1986).

The Carnmenellis granite has been the site of the first HDR research project in the UK with the aim of investigating reservoir stimulation. Initial work by the Camborne School of Mines, which has undertaken the project, showed that a shallow nrtificially fractured reservoir could be created at 300 m depth. The next step was to attempt to create a similar reservoir at 2000 m. This depth was chosen because it was deep enough to provide a realistic environment to test reservoir stimulation techniques but was within the capabilities of readily available drilling rigs. Two wells were drilled to the target depth in 1981. Both wells were deviated, with the production well (RH11) lying in a vertical plane above the injection well (RH12) with a vertical separation in the target area of 350 □ (Batchelor. 1985). RH12 was pre-treated using an explosive charge followed by hydraulic stimulation to

Microseismic monitoring during injection and the results of stress measurements showed that unfortunately the direction of maximum principal stress coincided with the direction of the wells and not with the joint set which the wells had been drilled to intercept. Therefore the effect of hydraulic fracturing was to create fractures in the plane of the wells, resulting in poor hydraulic connection between them. However the size of the reservoir created was significant - 1.5 km high, 1.2 km long and 400 m wide - and the experiment therefore showed that the large fractured volumes needed for HDR success could be created in UK granites.

Since 1983 a third well (RH15) has been drilled into the fractured reservoir. Although initial tests showed a poor connection between RH15 and RH12, this has been improved by using a large scale viscous injection in RH15. During subsequent water injection tests in RH12, at injection rates of 24 l/s recoveries from the other two wells have typically been in excess of 80 %, with a system impedence of 0.6 MPa/l/s (Camborne School of Mines, 1986). It is thought that the viscous fracturing treatment has stimulated existing joints in a cylindrical volume with dimensions approximately 70x70 x 200 m deep. More circulation tests have been undertaken recently and are planned to continue until 1987. Future plans for the site include drilling a borehole to a depth of around 5 km.

Outside south-west England the Weardale batholith has the most favourable HDR potential. Figure 3 shows that predicted sub-surface temperatures are lower than for the Cornubian batholith but considerably higher than those elswhere in the UK, in either granites or basement rocks. Figure 3 indicates that a temperature of 150 C might be reached at a depth of about 4.4 km and 200 C at about 6 km.

Heat flows over the granites in the Eastern Highlands of Scotland are low. leading to low predicted temperature gradients (e.g. the Ballater granite shown in Figure 3). It is unlikely therefore that these granites will offer much HDR potential.

LOW ENTHALPY RESOURCES IN SEDIMENTARY BASINS

Low enthalpy geothermal resources are available in the UK in the form of hot water (usually a very saline brine) present in the deeper parts of post-Carboniferous sedimentary basins (normally referred to as Mesozoic basins, although the oldest sediments that they contain are often of Permian age). These basins were initiated during late Carboniferous times when, during a period of uplift local downwarps developed. The basins developed during the Permian and Triassic periods and gradually filled with sediments, including thick sandstones near the base which are considered. to contain the most favourable aquifers for geothermal development. Figure 2 shows the locations of the basins, which in several cases are the onshore extensions of major offshore structures.

In the Mesozoic basins of southern Britain the comparatively low conductivity of some of the sedimentary rocks raises temperature gradients within the sediments to values similar to those predicted for the Cornubian and Weardale granites. (See for exnmple the east Lincolnshire profile in Figure 3). Thus temperatures in excess of 70 C can be achieved at 2 km depth.

The most favourable geothermal aquifers in the Mesozoic basins are the Permo-Triassic sandstones, both because they reach substantial depths in the basins and because they form good aquifers. Aquifer porosity and permeability decrease with depth as a result of fissure closure and cementation, but transmissivity values at depth are expected to be acceptable in several areas because of the large thicknesses of sandstones in the basins.

The potential of the Perno-Triassic sandstones as geothermal aquifers has been investigated by the British Geological Survey both regionally and in greater detail at specific sites. Estimating the geothermal resources of the aquifers involved defining the geometry and structure of the aquifers and evaluating their porosities, permeabilities and mean temperatures.

The quality of data used to estimate these parameters varied greatly, depending primarily on the extent of hydrocarbon exploration. In the Carlisle Basin, for example, only one borehole penetrated Permo-Triassic sediments at depth. compared with hundreds in the East Yorkshire nnd Lincolnshire Basin. In the latter basin the data are genernlly a few decades old, but in the Wessex Basin data are more recent, and modern comprehensive geophysical logging techniques have been used.

The geometry of the basins and the aquifers was delineated from previous work and the interpretation of were used as controls to study the thickness. depth and facies variations of the Yermo-Triassic sandstones.

Hydrogeological information at or near outcrop was obtained from rock samples and from water wells. At depth, borehole logs provided information such as porosity and fluid resistivity, and these interpreted values were occasionally suplemented by measurements of porositv and permeability and, rarely. of interstitial fluid chemistry from borehole core. Drill-stem tests and production tests are scarce but invaluable because they provide fluid samples and enable values of transmissivity. formation pressure and temperature to be measured in-situ. Deep boreholes providing core and test data in aquifers of geothermal interest are uncommon except where they have been drilled specifically for geothermal investigations. However work to aid geothermal studies has sometimes been commissioned in hydrocarbon boreholes.

As part of the programme of evaluation of the Permo-Triassic sandstones, three deep geothermal exploration wells were drilled on the basis of early results from the basin studies: at Harchwood near Southampton in the Wessex Basin, at Larne in Northern Ireland and at Cleethorpes. near Grimsby, in South Humberside in the East Yorkshire and Lincolnshire Basin. In addition a geothermal development well was drilled at Southampton for the Southampton City Council. The main purpose of the exploratory wells was to provide high-quality local data about the Permo-Triassic aquifers to facilitate geothermal evaluation, but it was also hoped to use the wells commercially if they proved the existence of an exploitable geothermal resource.

Information was obtained from the wells by means of a series of tests designed so that each test yielded progressively more data - or data applicable to a greater volume of aquifer - than its predecessor. Initially part or all of the aquifer was cored during drilling, providing lithological information, fluid samples and precise but localised values of porosity and permeability. Geophysical logging subsequent to drilling gave temperature values, a continuous profile of porosity, helped to identify permeable horizons, and indicated lithology in uncored parts of the aquifer. Drill-stem tests were then undertaken over selected intervals at Marchwood, Larne and Cleethorpes to give values of permeability, piezometric level and temperature, and to provide fluid samples. Gas-lift tests were carried out in each of the wells to develop the aquifer, to test well performance during pumping and to estimate transmissivity. Finally long-term production tests, carried out at Marchwood and at Southampton only, enabled data concerning temperature, transmissivity, well behaviour and fluid chemistry to be refined, and provided information about hydraulic boundaries.

Evaluation of resources

The geometries, hydraulic properties and temperatures of the geothermal aquifers in each Mesozoic basin have been used to estimate the potential geothermal resources of the basin. The "Geothermal Resource" (H_o) is defined as the heat in place in an aquifer in both the fluid and the matrix (Gale and others, 1984a). For a viable geothermal aquifer a minimum transmissivity of 5 darcy-metres (D.m) and a minimum temperature of 20 C have been prescribed. The geothermal resource is then taken to be the total amount of heat which would be released on cooling an aquifer from its mean temperature to the mean annual ground temperature. This calculation requires knowledge of factors such as porosity. density and specific heat for the aquifer and its contained fluid. A sensitivity analysis of potential errors in the determination of these variables has shown that for the Permo-Triassic sandstones in the UK the following equation is sufficiently accurate:

$$H = 2.6 \times 10^6 \, V \, (\theta_m - 10) \text{ joules} \qquad 3$$

where V (m^3) is the volume of the aquifer and θ_m is the mean temperature of the aquifer. The total geothermal resource cannot he recovered and therefore the "Identified Resource" is defined as the proportion of the geothermal resource that is likely to be available for economic exploitation in the future. It is calculated hv multiplying the geothermal resource by a maximum recoverv factor which takes account of rejection temperature, method of disposal of the fluid, and the hydraulic properties of the aquifer.

Results of evaluation

Five potential geothermal fields have been identified in the UK in Permo-Triassic sandstones (Figure 4). The geothermal and identified resources have been calculated for each basin and are summarised in Table 1. They have been calculated for areas where the temperature is greater than 40 C and where the transmissivity is

Calculations of identified resource assume that reinjection will be used, Where reinjection would not be used (for example at coastal sites) the identified resource would be reduced by a factor of about 2.5. If heat pumps were employed then a reject temperature of 10 C could be used and the identified resources would be approximately twice those shown in Table 1.

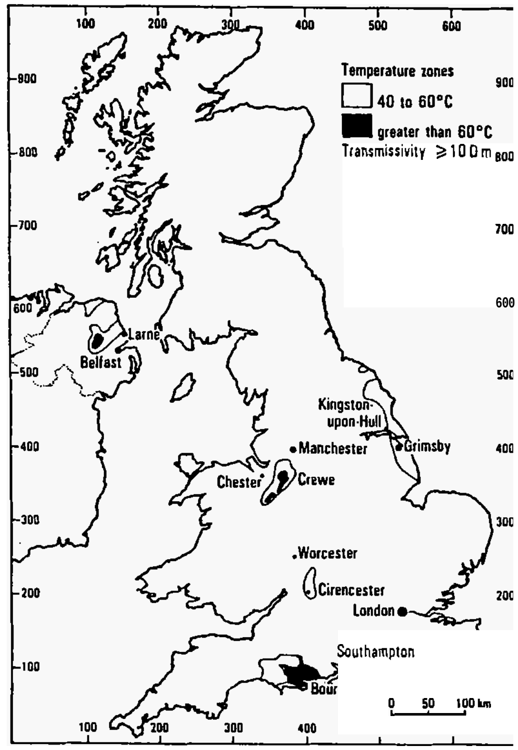

Figure 4. Potential low enthalpy geothermal fields in the UK as defined by a transmissivity of more than 10 D.m and a temperature of more than 40C. (From Downing and Gray, 1986).

TABLE 1

The resources of potential geothermal fields (From Allen, Gale and Price, 1985)

Basin	Formation*	Geothermal resource (exajoules**)	Identified resource***. (exajoules**)
E Yorkshire and Lincolnshire	SS	99	10.6
	BPS	6.1	0.9 †
Wessex	SS	22.9	3.2 ††
Worcester	P-T	12	1.4
Cheshire	SS	16.9	2.1
		27.9	3.8
N Ireland	SS	35.4	4.1
		220.8	26.7

* SS - Sherwood Sandstone
BPS - Basal Permian Sands
P-T - Permo-Triassic (undifferentiated)
P_t - Permian, including some Triassic

** 1 exajoule = 10^{18} joules

*** Identified resource calculated assuming reject temperature = 30C, direct use of fluid, reinjection of fluid.

† Transmissivity ≥ 5 D.m.

†† In part of area of transmissivity 5 to 10 D.m.

The main characteristics of Mesozoic basins containing a potential geothermal field are summarised below.

East Yorkshire and Lincolnshire Rasin

This basin contains two discrete potential geothermal aquifers which are overlain by a thick insulating laver resulting in temperature gradients of 26 to 30 C/km (Gale and others, 1983). The lower aquifer is the Basal Permian Sands which varies greatly in thickness, although consistent thicknesses of 30 to 60 m are attained in eastern Lincolnshire where the aquifer lies at a depth of about 1800 m. The sands are mainly aeolian and tend to be poorly cemented, having porosities of between 15 and 25 % and permeabilities 'averaging 100-200 mD. Where the aquifer is thick enough to form a resource the temperature varies from 50 C to greater than 60 C.

The shallower Sherwood Sandstone aquifer comprises up to 500 m of fluviatile deposits with porosities generally exceeding 20 % and permeabilities - evenly distributed throughout the sequence - of between a few hundred and a few thousand millidarcys. Transmissivities range from a few tens to several hundred darcy-metres and temperatures near the coast - where' the top of the aquifer lies at depths greater than 1000 m - are a little over 50 C.

The Cleethorpes Geothermal Well investigated the geothermal potential of both aquifers (Downing and others, 1985). The transmissivity of the Basal Permian Sands at that site was less than 2 D.m, with a temperature of 65 C. The transmissivity of the Sherwood Sandstone aquifer was found to be at least 60 D.m, and produced water during a gas-lift test at 53 C.

Wessex Basin

Of the I'ermo-Triassic sediments in this basin only the Sherwood Sandstone Croup is considered to have geothermal potential (Allen and Holloway, 1984). The Group attains a thickness of more than 250 m at a depth of about 1200 m and reaches a maximum depth of 2200m. The heat flow in the Wessex Basin is above average and sediments with low thermal conductivities lie above the Sherwood Sandstone. Group. Therefore temperature gradients are high. averaging 30 C/km over the basin; where the aquifer is deepest temperatures exceed 80 C.

The Sherwood Sandstone Croup is composed generallv of marginal and basal breccias which are well-cemented at depth, overlain by a series of fluviatile sand-dominated fining-upward cycles. The geothermal aquifer lies in these cycles and is composed of discrete zones of high permeability (commonly several darcys). Locally. interruption of the water-bearing layers, either by faulting or by lithological change may significantly affect the aquifer, particularly where it is thin. At Southampton, for example, the aquifer appears to be in an isolated block with an area of about 200 km (Downing and others, 1984).

Two geothermal wells have been drilled in the Wessex Basin, both in the Southampton area. The wells showed the Sherwood Sandstone Group to have a transmissivity of 3.5 D.m and to contain a brine with a salinity of around 100 g/l at a temperature of 76 C. Further west where the sandstones are thicker, transmissivities of the order of 20 D.m have been found. In the deepest parts of the basin temperatures exceed 80 C, but salinities are also high, reaching 300 g/l, which may cause problems in disposing of the brine after the heat has been extracted.

The Wessex Basin is considered to be the most favourable region for the development of low enthalpy resources above 60 C; however it is a predominantly rural area where the present distribution of heat loads is not favourable for widespread development.

Yorcester Basin

The Permo-Triassic sediments in the Worcester Basin are more than 1 km thick over most of the basin, and reach depths of more than 2.5 km (Smith and Burgess. 1984). However the temperature gradient is low. of the order of 18 C/km, and the maximum temperature reached is about 55 C. Nevertheless, with an average permeability of 100 mD the sandstones are hvdraulically attractive for the development of geothermal resources at temperatures up to 50 C.

Cheshire Basin

In the north of the Cheshire Rasin the Permo-Triassic sandstones form two distinct aquifers separated by the Manchester Marl (Gale and others, 1984b). To the south they coalesce to form a single unit. The total thickness of the sandstone exceeds 2.5 km and the maximum depth is more than 3 km. The largely arenaceous sequence has a low temoerature gradient of 17 C/km, leading to maximum

Transmissivities of the sandstones at depth are expected to exceed 10 D.m, but this is based on an interpretation Of geophysical logs.

Northern Ireland

Data for the Northern Ireland basins are limited but imply that the Sherwood Sandstone is the aquifer with the greatest geothermal potential (Bennett, 1983). It reaches thicknesses in excess of 500 m but is probably only permeable in the upper 200-250 m where transmlssivittes are likely to exceed 10 D.m. The temperature gradient is about 30 C/km and maximum temperatures are expected to be greater than 60 C - although in a largely rural area. The Larne well penetrated 650 m of Sherwood Sandstone in which the upper permeable zone had an estimated transmissivity of 8 D.m with a mean temperature of 40 C. The tower Permian Sandstone penetrated by the well was 440 m thick but had a very low transmissivity.

Other low enthalpy resources

The Permo-Triassic sandstones undoubtedly provide the best prospects for low enthalpy geothermal development in the UK. There are however other resources which may prove locally viable, for example the Lower Cretaceous Sandstones along part of the south coast of England where temperatures between 20 and 30 C may be reached. If a minimum temperature of 20 C for geothermal resources were acceptable then these sandstones could provide an identified resource of 1.6×10^{17} joules.

In addition, aquifers in the Upper Palaeozoic may possess some local geothermal potential. These rocks contain the only hydrothermal systems known in the UK, at Bath, Bristol. in Derbyshire and South Wales. These warm springs are all associated with the Carboniferous Limestone and their presence shows that fissures and circulation systems extend to depths up to 3 km. There are also Palaeozoic sandstones in the Midland Valley of Scotland and in north-east England which may have some geothermal potential.

REVIEW OF THE GEOTHERMAL POTENTIAL OF THE UK

The heat stored in the upper crust of the UK is considerable, despite the fact that it is a geologically stable area with an average heat flow similar to the world mean. The Accessible Resource Base - .the heat stored above mean ground temperature between the surface and a depth of 7 km - is 2.8×10^{23} joules (British Geological Survey 1985). The Hot Dry Rock Accessible Resource Base (the heat stored above 100 C at depths less than 7 km) is 36×10^{21} joules. These figures indicate the large potential that is available if the HDR concept proves to be viable.

Cornwall is recognised as being the best HDR target in the UK but the granites of northern England are also favourably placed. The temperature exceeds 200 C at a depth of 7 km only in these two areas and in small areas in Northern Ireland, and possibly Lancashire and Nottinghamshire.

The most favourable aquifers with low enthalpy geothermal potential in the UK are the Permo-Triassic sandstones. The geothermal resources of these sandstones at temperatures over 40 C are large, amounting to approximately 2.2×10^{20} joules. (If temperatures as low as 20 C are considered the resource is 4.7×10^{20} joules). Even if only the amount of energy which is likely to be exploitable at some time in the future is considered the value is 2.6×10^{19} joules. The latter figure is put into context when it is considered that approximately 10^{18}joules of electrical energy were generated in the UK in 1982 (Department of Energy. 1983). Most of the low enthalpy resources exist within areas designated as geothermal fields, where the transmissivity of the aquifer is expected to exceed 10 D.m and where favourable well yields might be expected without unacceptably high drawdowns.

Within these fields only brines with temperatures in excess of about 60 C could be used directly, or via a heat exchanger, for space heating and these therefore provide the most attractive resource. At lower temperatures heat pumps would be required to use the heat in the brine, thus increasing costs.

In conclusion, while it is clear that the geothermal resources of the UK do represent a significant energy resource, the extent to which they can be developed depends on whether the difficult engineering problems associated with the HDR concept can be overcome, whether appropriate heat pumps can be developed cheaply, and whether the costs of geothermal energy can become competitive with respect to those of other fuels.

ACKNOWLEDGEMENTS

The studies described in this paper hove been funded by the Commission of the European Communities and by the Department of Energy of Her Majesty's Government. The paper is published by permission of the Director, British Geological Survey (NERC).

REFERENCES

ALLEN DJ, GALE IN and PRICE M. 1985. Evaluation of the Permo-Triassic sandstones of the UK as geothermal aquifers. Hydrogeology in the service of man. Memoires of the 18 Congress of the IAH. Cambridge, Part 4, 12-22.

ALLEN DJ and HOLLOVAY S. 1984. The Wessex Basin.Investigation of the geothermal potential of the UK. British Geological Survey.

BATCIIELOR AS. 1982. An introduction to Hot Dry Rock geothermal energy. Journal of the Camborne School of Nines, 82, 26-30.

BATCHELOR AS. 1985. Hot Dry Eock reservoir stimulation in the UK: an extended summary. In "European Geothermal Update - Proceedings of the Third International Seminar on the results of EC Geothermal Energy Research. Munich, 1983." 681-711.Straub AS and Ungemach P (Eds). D Reidel Publishing Company.

BENNETT JRP. 1983. The sedimentary basins in Northern Ireland. Investigation of the geothermal potential of the UK. British Geological Survey.

BRITISH GEOLOGICAL SURVEY. 1985. Summary of the geothermal prospects for the United Kingdom. Investigation of the geothermal potential of the UK. British Geological Survey.

BURLEY AJ, EDMUNDS WM, ond GALE IN. 1984. Catalogue of geothermal data for the land area of the United Kingdom. Second revision April 1984. Investigation of the geothermal potential of the UK. British Geological Survev.

CAMBORNE SCHOOL OF MINES. 1986. A summarv of developments during phase 2B of the Camborne School of ?lines HDR project at Rosemanowes Quarry, Cornwall, 1983-1986. EEC/US Workshop on Hot Dry Rock. Erussels. Preprint.

DEPARTMENT OF ENERGY. 1983. Digest of United Kingdom Energy Statistics 1983. London. HMSO.

DOWNING RA, ALLEN DJ, BARKER JA, BURGESS WG, GRAY DA, and SMITH IF. 1984. Geothermal exploration at Southampton in the UK. A case study of a low enthalpy resource. Energy Exploration and Exploitation, 2, 327-342.

DOWNING RA, ALLEN DJ, BIRD MJ, GALE IN, and SMITH IF. 1985. The Cleethorpes Geothermal Well- a preliminary assessment of the resource. Investigation of the geothermal potential of the UK. British Geological Survey.

DOWNING RA and GRAY DA. 1986. Review of the geothermal potential of the UK. In "Geothermal energy - the potential in the United Kingdon." 151-161. Downing RA and Gray DA (Eds). HMSO.

DRURY MJ. 1984. Perturbations to temperature gradients by water flow in crystalline rock formations. Tectonophysics, 102, 19-32.

GALE IN, SMITH IF and DOWNING RA. 1983. The post-Carboniferous rocks of the East Yorkshire and Lincolnshire Basin. Investigation of the geothermal potential of the UK. British Geological Survey.

GALE IN, ROLLIN KE. DOWNING RA, ALLEN DJ and BURGESS WG. 1984a. An assessment of the geothermal resource8 of the United Kingdom. Investigation of the geothermal potential of the UK. British Geological Survey.

GALE IN, EVANS CJ, EVANS RB. SMITH IF, HOUGHTON MT and BURGESS WG. 1984b. The Permo-Triassic aquifers of the Cheshire and Vest Lancashire Basins. Investigation of the geothermal potential of the UK. British Geological Survey.

GALE IN and DOWNING RA. 1986. Heat flow and regional groundwater flow in the United Kingdom. Investigation of the geothermal potential of the UK. British Geological Survev.

KAPPELYEYER O. 1979. Implications of heat flow studies for geothermal energy prospects. In "Terrestrial Heat Flow in Europe." 126-135. Cermak V and Rybach

LEE MK. 1986. Hot Dry Rock. In "Geothermal Energy - the potential in the United Kingdom." 21-41. Downing RA and Gray DA (Eds). HMSO.

SMITH MC. 1375. The potential for the production of power from geothermal resouces. Report LA-UR-73-926. Los Alamos Scientific Laboratory. Los Alamos. USA.

SMITH IF and BURGESS WG. 1984. The Permo-Triassic rocks of the Worcester Basin. Investigation of the geothermal potential of the UK. British Geological Survey.

VHEILDON J and ROLLIN KE. 1986. Heat Flow. In "Geothermal Energy - the potential in the United Kingdom," 8-20. Downing RA and Gray DA (Eds). HMSO.