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Geothermal resources of the United Kingdom

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Abstract: Geothermal prospects in the UK are represented by low enthalpy resources in deep sedimentary basins and 'Hot Dry Rock' (HDR) resources in radiothermal granites, and possibly in deep basement rocks where they are overlain by thick low conductivity sediments. The low enthalpy resources are in Permo-Triassic sandstones at temperatures of more than 40 °C. Four deep exploration wells have been drilled to investigate the potential of these sedimentary aquifers. The main HDR resource potential is associated with major granite batholiths in southwest and northern England where temperatures are predicted to be 200 °C at about 5.4 and 6 km respectively. The HDR potential is being investigated by the Camborne School of Mines at their test site in Cornwall where three boreholes have been drilled to depths of between 2 and 2.5 km.

The Hot Dry Rock Accessible Resource Base at temperatures of more than 100 °C and depths of less than 7 km is 36×10^{21} joules (equivalent to 130×10^4 million tons of coal). The low enthalpy Geothermal Resource of the Permo-Triassic sandstones at temperatures of more than 40 °C is 200×10^{18} joules (equivalent to about 8000 million tons of coal). If only a small fraction of these resources could be developed, it would be significant in terms of the UK's energy balance.

Following the marked increase in energy prices in the mid-1970s, the United Kingdom, in common with many other countries, began to assess the potential of alternative forms of energy, including geothermal energy (Dunham 1974). Britain had not previously been associated with the development of geothermal energy for it is remote from plate boundaries and the associated volcanic and tectonic zones, in which geothermal energy resources are more usually developed. Britain forms part of the stable foreland of Europe and the last period of igneous activity was some 50 to 55 million years ago in the Tertiary. The average heat flow is similar to that for 'normal' continental areas but, nevertheless, the geothermal gradient exceeds 25 °C/km in many areas and can exceed 30 °C/km, values that give temperatures of more than 60 °C at a depth of 2 km and possibly 100 °C at 3 km; such temperatures are suitable for direct heating applications for space heating, industrial processes and horticulture. As a result of favourable initial assessments, the British Geological Survey (BGS) was commissioned by the Department of Energy and the Commission of the European Communities to assess the geothermal potential of the UK by the mid-1980s. This paper summarizes the results of the programme carried out between 1977 and 1984 and which is reviewed in more detail by Downing & Gray (1986). Basically the programme comprised (a) a study of the heat flow pattern in the UK, (b) an investigation of the low enthalpy (that is low temperature) potential of hot groundwaters in aquifers, particularly in Mesozoic basins but also in Upper Palaeozoic basins, and (c) an assessment of the potential of major granite intrusions as sources of geothermal energy from 'Hot Dry Rocks' (HDR), by circulating water through artificially created fractures in the rock.

The only low enthalpy resources discussed in this paper are those at temperatures of more than 40 °C but it should not be overlooked that very large amounts of thermal energy are stored in groundwater at less than this temperature; as much as 245×10^{18} joules occur in the UK between 20 and 40 °C. These low temperature waters, as is also the case with waters between 40 and 60 °C, can only be developed with the assistance of heat pumps. In many parts of Europe and North America, shallow groundwater at depths of less than 30 to 40 m, at low but very advantageous constant temperatures (e.g. 11 °C in the UK), is being used as an energy source. This form of heating has not yet captured the imagination in the UK and there are few applications, although BGS has prototype schemes heating greenhouses in Cambridgeshire and domestic houses at Irvine New Town in Scotland (Day & Kitching 1981).

Geothermal schemes are capital intensive and most of the capital is needed in the initial stages for drilling and other engineering works. Running costs are relatively small, being restricted to costs for pumping, depreciation and maintenance. The cost effectiveness of a geothermal scheme depends upon the amount of heat that can be recovered which is a function of the flow rate, the heat capacity of the fluid and the temperature drop as the heat is extracted by heat exchangers and heat pumps. The high capital investment implies that a minimum amount of heat must be sold to make a scheme economic and this sets a lower limit to acceptable flow rates and hence the transmissivity of the reservoir. The extent to which a resource can be exploited is related to the availability of suitable heat loads; unfortunately low enthalpy geothermal resources are in predominantly rural areas where heat loads are restricted to major towns, or possibly large horticultural enterprises. HDR resources do not have this disadvantage if they are at temperatures suitable for electricity generation.

Heat flow and its implications

Many measurements of sub-surface heat flow have been made in the UK since 1868, when a 'Committee on strata temperatures' formed by the British Association issued the first of a series of 23 reports incorporating measurements from a variety of sources. Observations gradually increased in number and reliability as theoretical research on crustal heat flow developed (e.g. Bullard & Niblett 1951). More recently major programmes of research were mounted at Imperial College, London and at Oxford University directed at both scientific objectives (e.g. Tammemagi & Wheildon 1974; Richardson & Oxburgh 1978) and applied geothermal studies (e.g. Oxburgh *et al.* 1980; Wheildon *et al.* 1980). All available heat flow data have now been catalogued (Burley *et al.* 1984) as a component part of the broader BGS geothermal programme.

By 1985 heat flow had been reliably calculated at 188 sites in the UK, commonly in specially constructed boreholes about 200 to 300 m deep. Equilibrium temperature gradients were measured in the boreholes and the thermal conductivity of samples collected throughout the sequences was also measured. To obtain a better understanding of the regional variation, the calculated values were supplemented with estimates of heat flow at sites where temperature measurements were available at known depths and where the geological sequence was also known. The thermal conductivities of the various formations in the borehole sequences were deduced from a data-file for mean conductivities of the principal geological formations in the UK (Rollin, in Gale *et al.* 1984*a*). After excluding less reliable values, about 100 estimated values were used, together with the 188 calculated values, to produce the heat flow map in Fig. 1.

The overall heat flow pattern is one of regional anomalies superimposed on a fairly uniform background field of about 52 mW/m^2 (Wheildon & Rollin, in Downing & Gray 1986). The principal anomalies, where maximum values are up to twice the background value, are associated with major granitoid batholiths in Cornwall and northern England. Values are also above the regional value in the batholith in the Eastern Highlands of Scotland, although the maximum recorded value is only 76 mW/m^2. In sedimentary basins above-average values occur in Lincolnshire, Wessex, Gloucestershire, as well as the Midland Valley of Scotland, and over large parts of Northern Ireland. The high heat flows associated with the granitoid batholiths are caused by the presence of above average, but trace amounts of the heat-producing radioactive isotopes of the elements uranium, thorium and potassium, whereas the anomalies associated with the sedimentary basins are considered to be caused by groundwater acting as a heat transfer medium and redistributing heat as it rises to shallower depths in regional flow systems.

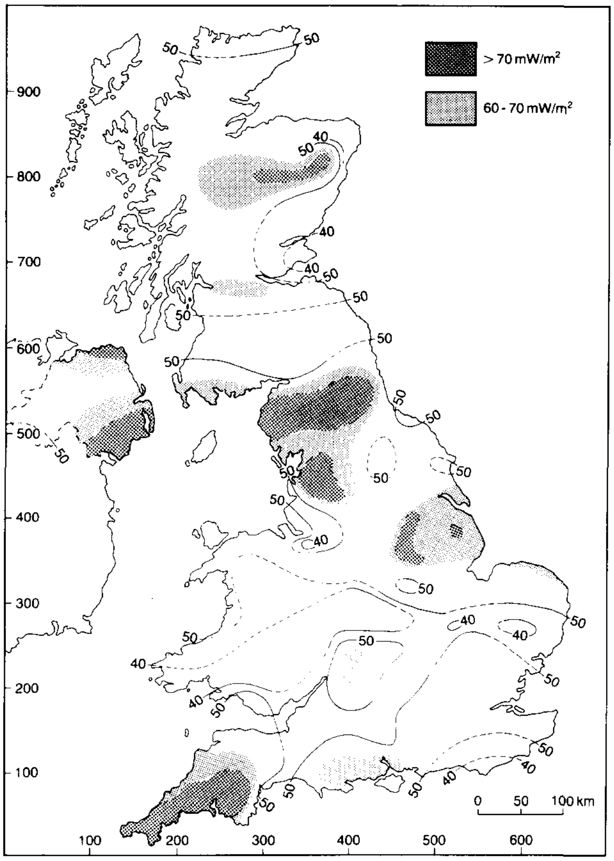

Fig. 1. Heat flow map of the United Kingdom (units are mW/m^2).

From the practical point of view two features are evident from an examination of the heat flow field—first, the anomalies associated with radiothermal granites and second, those associated with sedimentary sequences in the East Midlands of England, southern England (the Wessex Basin) and western England (the Worcester Basin). The relationship of the geology of the UK to the heat flow anomalies indicates that geothermal energy could possibly be derived from two sources:

(1) hot groundwaters in permeable rocks in deep sedimentary basins. Temperatures of more than 60 °C are attained in several basins at depths of 2 km. If heat pumps could be incorporated into heating systems then water at more than 40 °C could be used; temperatures of more than 40 °C occur at depths of about 1 km;

(2) heat stored in impermeable rocks at temperatures of more than 100 °C, which, in general terms, occur at depths of more than 3.3 km.

Aquifers in Mesozoic and Palaeozoic sequences are possible sources of hot water and the radiothermal batholiths of Cornwall and northern England are favourable areas for the development of high temperature hot dry rock resources. Under favourable conditions, discussed later, the deep basement rocks of eastern and southern England may also be suitable as hot dry rock reservoirs.

Low enthalpy resources in sedimentary basins

Potential geothermal reservoirs are found in several deep Mesozoic sedimentary basins in the UK (Fig. 2) and in these basins the most favourable formations are the sandstones of the Permian and Triassic. Upper Palaeozoic sequences below the Permian also contain potential reservoirs and in fact these rocks yield the only warm springs in the UK. The Bath Spring is the best known with water issuing at 10 l/s at a temperature of 46 °C. The spring is the outlet of a groundwater circulation system that ascends from a depth of 3 to 4 km (Andrews *et al.* 1982). However, generally the Upper Palaeozoic reservoirs are hard compact rocks with permeabilities of less than 10 millidarcies (mD) and commonly less than 1 mD; water flows through them mainly in fractures and fissures. Where properties are more favourable, as possibly in the Midland Valley of Scotland and in northeast England, they could have potential but the details are not discussed in this review, which concentrates on the work undertaken in the more favourable Permo-Triassic sandstones in the principal Mesozoic Basins containing water at more than 40 °C.

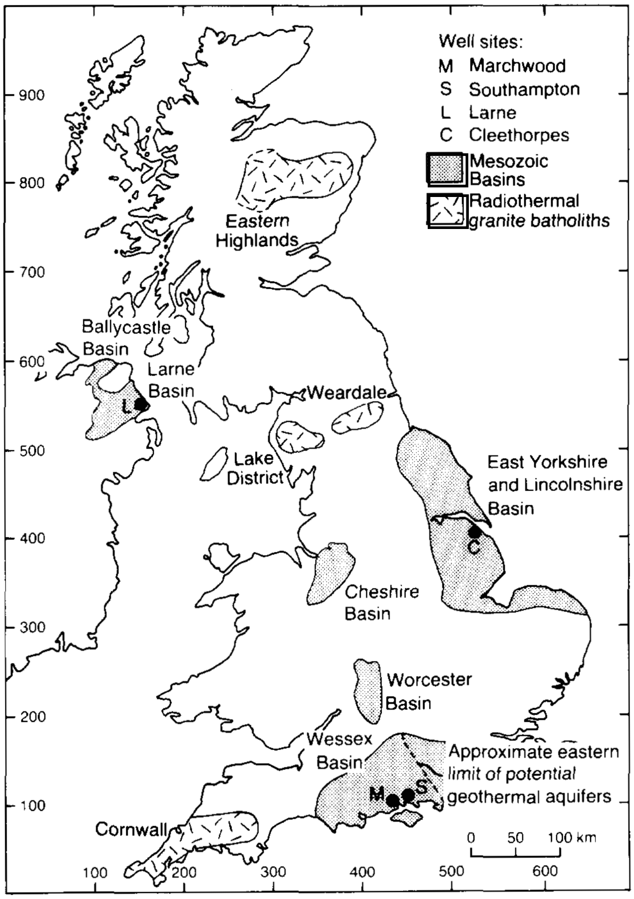

Fig. 2. Mesozoic basins containing geothermal resources at temperatures higher than 40 °C and locations of major radiothermal granites.

East Yorkshire and Lincolnshire Basin

In this basin the Triassic Sherwood Sandstone is separated from the Basal Permian Sands by an evaporite sequence and the two sandstones form distinct reservoirs (Gale *et al.* 1983). The Sherwood Sandstone attains a maximum thickness of over 500 m. The porosity generally exceeds 20% and the average permeability is considered to be about 250 mD. Over extensive areas the transmissivity is more than 70 Dm (darcy metres). The sandstone contains a very large geothermal resource at temperatures of 40 to over 50 °C (Fig. 3). The Basal Permian Sands are much thinner with a maximum thickness of 60 m in east Lincolnshire. Generally they are believed to be of aeolian origin which gives them favourable aquifer properties, but though the typical value for permeability is 150 mD the relatively low thickness means that maximum transmissivities are only about 10 Dm. Maximum temperatures in these sands exceed 60 °C (Fig. 3). The nature of the two reservoirs was investigated with the Cleethorpes No 1 Well, drilled in 1984 on the south Humberside coast. The data derived from this well are summarized in the following section but, while the Sherwood Sandstone proved to be a good reservoir, the Basal Permian Sands had a disappointingly low transmissivity.

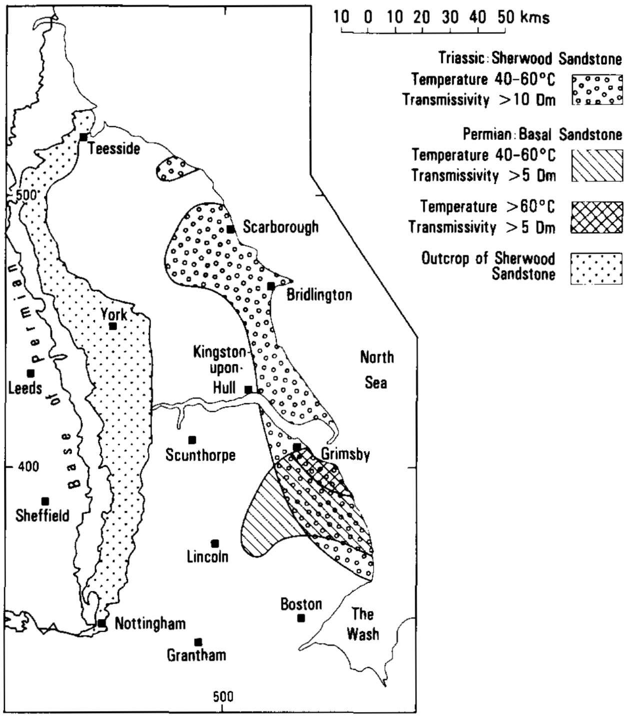

Fig. 3. Low enthalpy geothermal resources of the Permo-Triassic sandstones in the East Yorkshire and Lincolnshire Basin.

Wessex Basin

The geological prospects for geothermal development are very favourable in this basin (Allen & Holloway 1984). The only reservoir is the Sherwood Sandstone which attains some 200 to 250 m in the west. The sandstone contains thin discrete permeable horizons with values up to about 5 mD and maximum transmissivities are of the order of 10 to 20 Dm. Water at temperatures ranging from 40 to 60 °C and at over 60 °C occurs over significant areas (Fig. 4).

The Sherwood Sandstone, as a potential geothermal

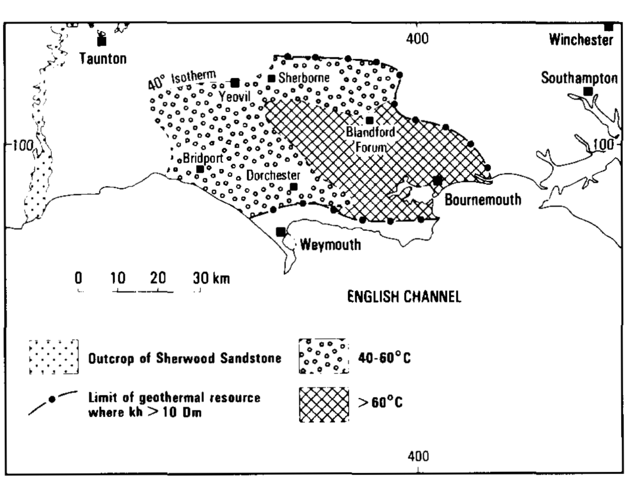

Fig. 4. Low enthalpy geothermal resources of the Sherwood Sandstone in the Wessex Basin. Development would be practicable in the area indicated by ornaments.

reservoir, has been investigated by two wells in, and to the immediate west of, Southampton (Downing *et al.* 1984). These proved to be sited near the eastern margin of the sandstone basin where the thickness was only about 60 m of which only some 6 to 16 m represented zones of high permeability. Prospects are more favourable further west.

Worcester Basin

The Permo-Triassic sandstones are over 1000 m thick over most of this basin and include two main reservoirs. The aquifer properties are very favourable because of the presence of individual sandstones with high permeabilities, and the maximum transmissivities of each reservoir can be of the order of 80 Dm (Smith & Burgess 1984). Because the insulating cover of low permeability sediments is thin and the geothermal gradient in the sandstone is no more than 18 °C/km, the temperature only attains 55 °C in the deepest parts of the basin. However, large volumes of groundwater occur at temperatures of 40 to 50 °C and represent a significant resource.

Cheshire Basin

The geothermal gradient in this basin is low, and values of less than 20 °C/km are characteristic (Gale *et al.* 1984*b*). As a consequence deep wells would be required to obtain useful temperatures. However, the Permo-Triassic sandstones are over 2500 m thick and lie at depths of more than 3000 m where the temperature exceeds 60 °C with maximum values of up to 80 °C. Over extensive areas waters occur in the 40 to 60 °C range. The transmissivity is believed to exceed 10 Dm although this is based on an interpretation of geophysical logs and not direct test data.

Northern Ireland

Two deep Permo-Triassic basins exist in Northern Ireland in which the Triassic Sherwood Sandstone is separated from the underlying Permian sandstones by marls, limestones and evaporites. The Sherwood Sandstone is over 500 m thick but the producing thickness is much less, probably of the order of 200 to 250 m and tending to occur at or close to the top of the formation (Bennett 1983). The average transmissivity is considered to be 10 to 20 Dm. Temperatures in the producing zone of the sandstone are thought to exceed 60 °C in only a small area near Lough Neagh but water in the sandstones at temperatures of 40 to 60 °C occurs over appreciable areas.

The distribution and thickness of the Permian sandstones is not well known although they have yielded brines at more than 60 °C from drill-stem tests. The current view of prospects for geothermal energy in Northern Ireland is influenced by data from the Larne No 2 exploration well which may be atypical of the area as a whole. This well encountered over 250 m of water-bearing Sherwood Sandstone containing water at 40 °C but the transmissivity was only 7 Dm and below the mean for the region as a whole. It also intersected nearly 450 m of Lower Permian Sandstone which included coarse-grained aeolian sandstones, but the porosity was less than 12% and the transmissivity very low because of an extensive development of diagenetic cement.

Low enthalpy test wells

Four deep geothermal wells have been drilled to investigate the nature of the Permo-Triassic sandstones and their potential as geothermal reservoirs (Fig. 2) and many associated investigations, including drill-stem tests, have been carried out in hydrocarbon exploration boreholes. The principal features of the four geothermal wells are given in Table 1. At each site only one well has been drilled, but long-term development would generally require a second well to re-inject the water into the aquifer after heat had been extracted. This is not only because deep groundwaters from the Permo-Triassic are invariably very saline but also because the injection process maintains the pressure in the reservoir and the injected water is again heated by contact

Table 1. *Principal details of geothermal wells in the UK*

	Marchwood	Southampton	Larne		Cleethorpes	
Status of well	Exploration	Development	Exploration		Exploration	
Basin	Wessex	Wessex	Northern Ireland		Lincolnshire	
Total depth m	2617	1827	2880		2100	
Target	Triassic sandstones	Triassic sandstones	Triassic sandstones	Permian sandstones	Triassic sandstones	Basal Permian Sands
Depth of reservoir m	1666–1725	1729–1796	968–1616	1823–2264	1100–1497	1865–1891
Thickness of reservoir m	59	67	648	441	397	26
Thickness of pay zone m	6	16	286	Virtually nil	250	8.5
Completion details	Well Screen	Open-hole	Cased off	Perforated casing	Cased off	Open-hole
Transmissivity Dm	4	3.3	7	<1	>60	<2
Reservoir temperature °C	73.6	76	40	65	53	64
Well head temperature °C	71.6	74	—	—	c.50	—
Bottom hole temperature °C	84.6	76.2	—	91.2	—	68
Flow rate of test l/s	30	20	—	—	20	—
Pressure reduction after 30 days MN/m^2	3.7	3.1	—	—	c.0.60*	—
Salinity of water g/l	103	125	200	—	35–80	c.230

* After 15 hours.

with the aquifer matrix and sweeps heat towards the abstraction well; most of the heat is actually stored in the rocks rather than the water they contain. Two-well systems, referred to as doublets, have been successful in the Paris Basin (Haenel 1983) where over 30 geothermal schemes are in use for district heating purposes.

Evaluating deep wells by long term production tests is very expensive and can be contemplated only after preliminary assessments have indicated reasonable prospects of the well providing an adequate economic flow of brine. The testing sequence adopted for the wells was:

(a) core sampling of selected intervals to examine the lithology of potential aquifers and the nature of the rock matrix, to provide samples for laboratory measurements of aquifer properties and for extraction of pore waters for chemical analysis;
(b) interpretation of geophysical logs to give, in particular, porosities, downhole temperatures and locations of potential permeable zones;
(c) drill-stem tests of selected intervals to investigate the distribution of permeability, to give aquifer pressure and temperature, to estimate transmissivity and to provide a sample of the formation water;
(d) gas-lift test (of about three to four days) to develop the well, to provide an assessment of the yield of the well, to derive the transmissivity of the aquifer and the temperature of the water and to define specifications for a suitable pumping unit;
(e) longer-term production test (of about 30 days) to derive well characteristics and aquifer properties, identify any flow barriers near the well, measure a stable reservoir temperature, make an initial assessment of the size of the geothermal resource and to provide data for a preliminary predictive management model of the geothermal yield potential of the well.

Each stage produces data of greater reliability but at greater cost. These tests provide details of the reservoir characteristics and allow a preliminary evaluation of the production capacity of the well but the final assessment can only be made after longer-term data have been accumulated from more extensive production periods.

The two wells in or near Southampton, of which the first was a 'wildcat', are near the edge of the Triassic basin of deposition in the Wessex Basin and the transmissivity of the sandstone reservoir was found to be only about 4 Dm. Both wells have yielded 30 l/s at about 75 °C, albeit for large pressure reductions of the order of 3.7 MN/m^2 (equivalent to a drawdown of water level of about 350 m). Extensive tests and subsequent computer modelling indicated that the wells are probably in a block of some 200 km^2 with impermeable boundaries (Allen *et al.* 1983; Downing *et al.* 1984; Price & Allen 1984). This reduced the long-term yield to about 10 l/s from a single well used without re-injection and ruled out the original plans for a group heating scheme in the city centre. Nevertheless, even the reduced yield would be adequate to supply the Civic Centre and the City Baths, and such a scheme may yet prove viable.

The well at Larne was also the first deep geothermal well into the Permo-Triassic basins in Northern Ireland. It was disappointing in that although 440 m of Lower Permian Sandstone were encountered, they proved to be very cemented with negligible permeability. The well at Cleethorpes penetrated a very permeable Sherwood Sandstone sequence some 400 m thick which, on test, yielded 20 l/s at 53 °C for a water level drawdown of less than 7 m; the transmissivity derived from a gas-lift test was 60 Dm, although core analysis and interpretation of geophysical logs suggested it may be as much as 200 Dm. The deeper and hotter Basal Permian Sands were some 30% thinner than expected. The 26 m thickness included 20 m of fluviatile sands rather than the 30 m of aeolian sands that had been anticipated and the main water-bearing horizons were only 8.5 m thick; as a consequence the transmissivity was less than 2 Dm (Downing *et al.* 1985).

Hot dry rock reservoirs

The permeability of rocks decreases with increasing depth and generally low enthalpy resources are restricted to formations at depths of less than three to four kilometres. Most rocks are essentially impermeable at greater depths. The feasibility of using the heat stored in deep impermeable rocks, referred to as the Hot Dry Rock concept, it being investigated by large-scale field experiments in New Mexico by the Los Alamos National Laboratory, and in Cornwall by the Camborne School of Mines. The programmes involve drilling two or more boreholes to depths where appropriate temperatures occur and creating artificial fracture systems between them by injecting water under high pressure. Water is then circulated down one borehole to extract heat from the fractured zone, which acts as a natural heat exchanger, before returning to the surface as hot water or steam.

The recognition that high heat flows are associated with radiothermal granites has resulted in attention being given to granite rocks as HDR targets. In such granites, temperatures of 200 °C can be anticipated at depths of 6 to 7 km. The Hercynian batholith in southwest England (Fig. 2) was the first to be recognized in this respect in the UK (Dunham 1974) but other granites could also have potential as well as basement rocks generally, especially if HDR development proves possible for combined heat and power schemes rather than entirely for use at the high temperatures needed for the generation of electricity.

In granitic rocks, all other things being equal, it is recognized that surface heat flow increases with heat production from the radioactive isotopes of uranium, thorium and potassium. Thus the principal preliminary requirements for an HDR target are a high heat production and a large intrusive volume with a vertical extent to many kilometres as indicated by negative gravity anomalies (Brown *et al.* 1979; Lee *et al.* 1984).

The gravity and heat production data for the UK identify three areas as satisfying the preliminary criteria for a possible HDR target:

(1) The Hercynian batholith in southwest England.
(2) The Caledonian granites of northern England.
(3) The Caledonian granites of the Eastern Highlands of Scotland (Fig. 2).

The southwest England batholith has been recognized for some years as a possible HDR target and it has been extensively studied from this point of view. A detailed field study by the Camborne School of Mines is now in progress at a site on the Carnmenellis intrusion near Falmouth. Three boreholes have been drilled to depths of 2 to 2.5 km to investigate the feasibility of creating HDR reservoirs by combined explosive and hydraulic fracturing (Batchelor 1983). The present stage of the work is concerned with creating suitable heat exchange surfaces in the granite by the stimulation of existing fractures and planes of weakness rather than attempting to prove a system at temperatures of 200 °C.

The heat flow over the batholith is generally greater than 110 mW/m^2, about twice the national average, and heat production is also uniformly high with average values of 4.0 to 5.3 μW/m^3. It is estimated that a temperature of 200 °C might be attained in the granite at a depth of about 5.4 km.

Much less is known about the heat flow and heat production in the two major granites in northern England—the Lake District and Weardale granites (Fig. 2). As part of the present programme the heat flow has been measured at two sites in the Lake District (values being 78 and 101 mW/m^2) and a value is also available at one site in the Weardale Granite (95 mW/m^2). The heat production in the Lake District is about 4 to 5 μW/m^3 and somewhat less than 4 μW/m^3 in the Weardale Granite. Estimating the HDR potential from such limited data is clearly uncertain but the temperature could be 200 °C at a depth of 6 km in the Weardale Granite although possibly only 150 to 160 °C in the Lake District (Lee *et al.* 1984).

The heat flow in the Eastern Highlands batholith is elevated compared with the rest of northern Scotland but ranges only from about 60 to 75 mW/m^2 despite high heat production of 5 to 7 μW/m^3. The reason is thought to be two-fold; firstly the area has a lower background heat flow than southwest England and secondly, the concentration of heat-producing elements may decline relatively rapidly with depth. As a consequence these granites are not suitable HDR targets.

To date, studies of HDR potential in the UK have been concerned primarily with the prospects in radiothermal granites with the objective of identifying areas where temperatures of 150 to 200 °C might be attained at depths of less than 6 to 7 km (Fig. 5). If lower temperatures were acceptable then basement rocks could also have potential. The value of heat flow in basement rocks is about 52 mW/m^2 and this, together with their relatively high thermal conductivity, results in low geothermal gradients of the order of 15 °C/km. However, where they are buried below thick insulating cover of low conductivity Mesozoic and Upper Palaeozoic sediments, the geothermal gradient is raised to values similar to those found in the Cornubian and Weardale granites. In eastern England such favourable conditions give temperatures of about 150 °C at a depth of 6 km and a similar situation exists in the Wessex Basin. Areas where temperatures of 100 °C could be attained at depths of less than 4 km are shown in Fig. 6. A programme is now in hand to assess the potential of basement rocks under the main urban areas of the country.

Assessment of the geothermal resources

The Accessible Resource Base (ARB), defined as the heat stored at more than the mean ground temperature (10 °C in the UK) and above a depth of 7 km, is 2.75×10^{23} joules, a mean value of 1.07×10^{18} joules/km^2. The Hot Dry Rock ARB, the heat stored at more than 100 °C and at less than 7 km, is 36×10^{21} joules (Gale *et al.* 1984*a*). These figures indicate the total heat store and not the amount that could be recovered. But, if only 1% of the HDR ARB could be developed (ETSU 1982), this would amount to 360×10^{18} joules (equivalent to about 13000 million tons of coal), a figure that reflects the potential available if the HDR concept could be turned into economic reality.

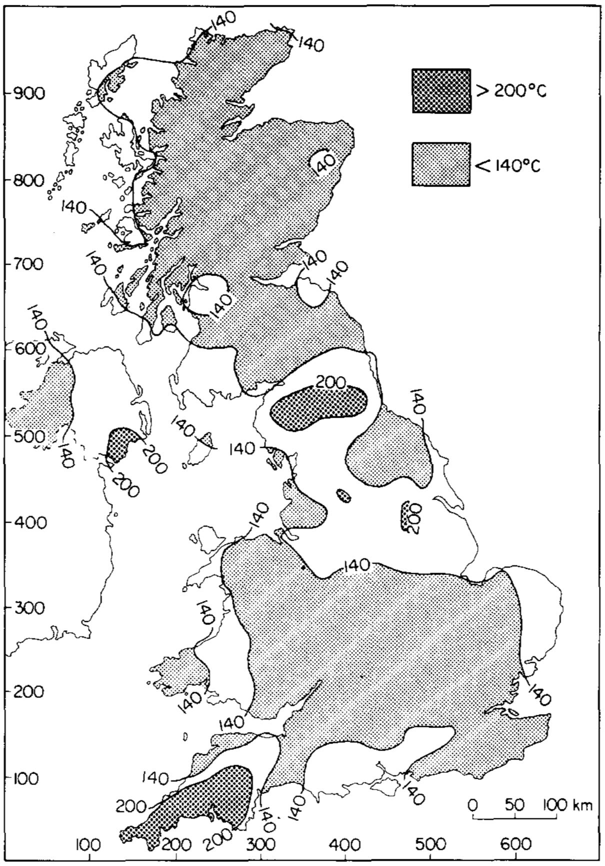

Fig. 5. Estimated temperature at a depth of 7 km in the United Kingdom (contours in °C).

With regard to the low enthalpy resources, the Geothermal Resources of each aquifer have been estimated from:

$$[\phi\rho_w C_w + (1-\phi)\rho_m C_m]V(\theta_m - \theta_g)$$

where ϕ is the porosity of the aquifer, ρ_w and ρ_m are the densities of water and the rock matrix, C_w and C_m are the specific heats of water and the rock matrix, V is the volume of the aquifer, θ_m is the mean temperature of the aquifer and θ_g is the mean annual ground temperature. The total Geothermal Resources of the Permo-Triassic sandstones at temperatures of more than 40 °C amount to 220×10^{18} joules. This represents the total heat stored in the aquifers and it could not all be used. The proportion more likely to be available for development is referred to as the Identified Resources and is derived from the Geothermal Resources by applying a maximum recovery factor of:

$$[(\theta_m - \theta_r)/(\theta_m - \theta_g)]F$$

where θ_r is the reject temperature of the heat extraction system and F is a factor related to the aquifer properties and the method of extracting the hot water (Lavigne 1978); in the UK a value of 0.25 has been assumed when development is by a doublet system comprising an abstraction and an injection well. The Identified Resources at temperatures of more than 60 °C, assuming development

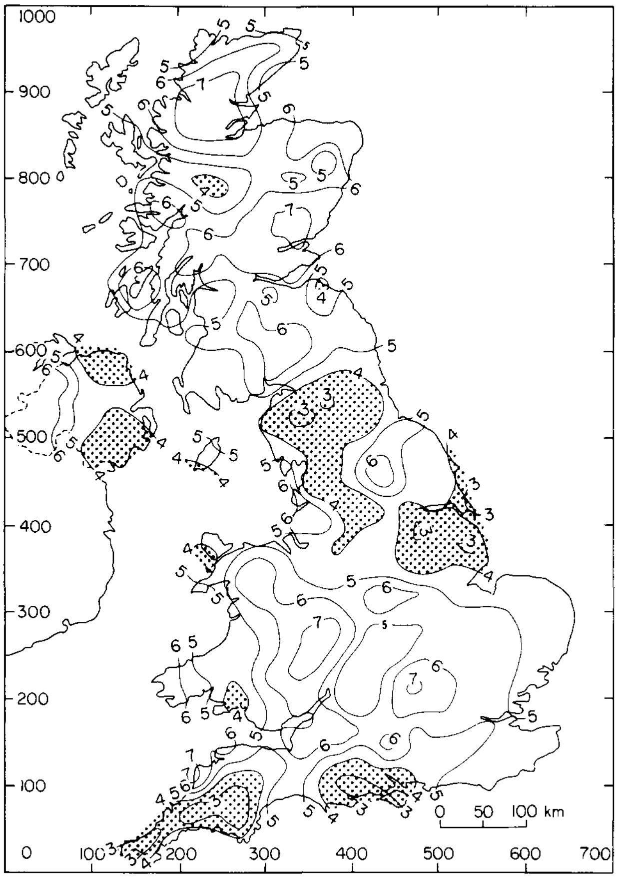

Fig. 6. Depth in kilometres to the 100 °C isotherm in the United Kingdom (areas less than 4 km stippled).

with doublets and rejection at 30 °C, are 5 × 10^{18} joules. The resources in the temperature range 40 to 60 °C, again assuming the use of doublets but incorporating heat pumps, thereby allowing rejection at 10 °C, amounts to 48 × 10^{18} joules. The Identified Resources are summarized in Table 2, expressed as joules and million tons of coal equivalent.

Conclusions

Despite the fact that geologically speaking the UK is a stable area, the heat store in the crust within acceptable drilling depths is considerable, and it may be feasible to develop the thermal energy stored in hot impermeable (or dry) rocks and in hot groundwaters in permeable rocks. The future potential of HDR resources must await the outcome of the major field experiments being carried out in New Mexico, USA, and in Cornwall, England but, if these prove successful, the most favourable development areas in the UK are the radiothermal granites in Cornwall and northern England where 200 °C may be attained at less than 6 km. A hot dry rock doublet developing a reservoir at 200 °C for electricity generation could yield about 3.5 MW of electrical power or perhaps 12 MW from five doublets at a single site. Potential at lower temperatures, say 100 °C, could exist in basement rocks at depths of less than 4 km beneath thick insulating sedimentary cover in, for example, eastern and southern England. With this in mind BGS is currently studying the deep geology beneath several major conurbations.

Table 2. *Identified Resources of the Permo-Triassic sandstones at temperatures of over 40 °C*

	Temperature °C			
	40–60*		60†	
	10^{18} joules	Mtce	10^{18} joules	Mtce
East Yorkshire and Lincolnshire	26.2	974	0.2	7
Wessex	2.8	105	1.8	69
Worcester	3.0	112	—	—
Cheshire	8.9	331	1.5	56
Northern Ireland	6.7	249	1.3	48
Totals	47.6	1771	4.8	180

Estimates assume development with doublets.

* Use of heat pumps assumed and hence a reject temperature of 10 °C.

† Assumes heat pumps would not be used and hence rejection at 30 °C.

Mtce is million tons of coal equivalent.

A scale is given to the figures by bearing in mind that the annual use of electrical energy in the UK is about 10^{18} joules.

The most favourable exploration areas for low enthalpy resources in the Permo-Triassic sandstones have been identified as 'potential geothermal fields' using the criteria of a temperature greater than 40 °C and a transmissivity of more than 10 Dm (Fig. 7). Most of the heat is stored

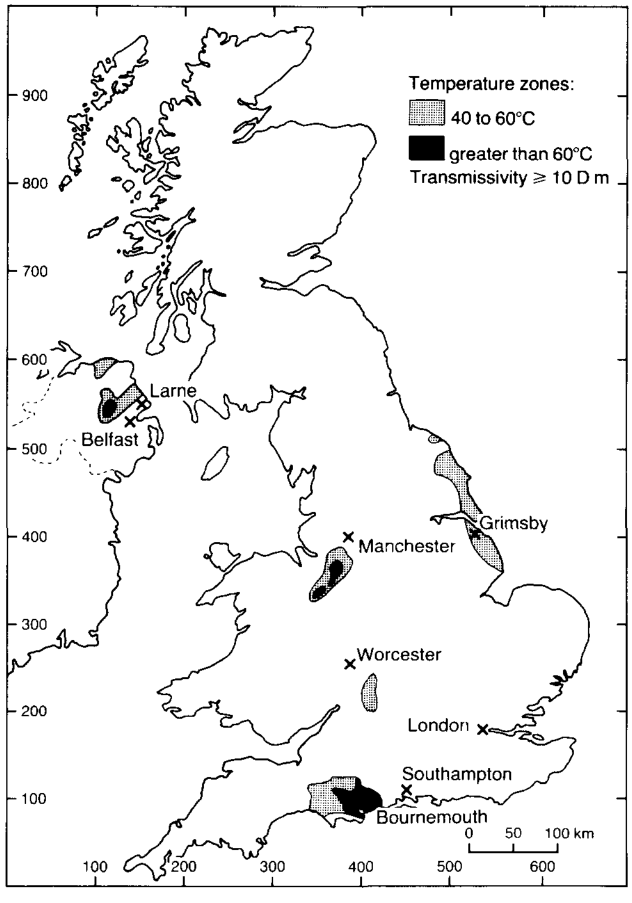

Fig. 7. Potential low enthalpy geothermal fields in the UK. Defined by a temperature of more than 40 °C and a transmissivity of more than 10 Dm.

between 40 and 60 °C at relatively shallow depths in rocks with favourable reservoir properties. Over 50% of the Identified Resources in this temperature range are in the Sherwood Sandstone of East Yorkshire and Lincolnshire which represents the major, readily accessible, low enthalpy heat store in the UK, equivalent to almost 1000 million tons of coal. But widespread development of this resource depends upon an improvement in the coefficient of performance of heat pumps, as well as wider experience of their use, and a more general acceptance of district heating schemes. Water at directly useful temperatures of over 60 °C is more restricted in distribution and the most favourable area is in the west of the Wessex Basin.

The resources represent heat stored in reservoirs that cover very extensive areas and only part of this heat could be used realistically. The distribution of the resources is also predominantly in rural areas although a number of major towns occur within potential geothermal fields. Development would be likely to start at individual favourable sites where heat loads exist and, if successful, expand into small well-fields in relatively restricted areas. In this manner the resource estimates would become more reliable and an assessment of the reserves could be made. A doublet developing a low enthalpy reservoir at, say, 75 °C and rejecting the water after use at 30 °C could yield some 5 MW of thermal energy, a yield that is very significant on a local scale.

The studies in the UK have indicated that the Permo-Triassic sandstones can yield the high flow rates required for successful development and economic schemes are feasible in favourable situations. At present, however, commercial development is constrained by the uncertainty as to whether or not an individual reservoir can produce over a long period of time and whether re-injection wells in sandstones can be effective and economic. The legal status of geothermal energy also remains uncertain as it is not covered by any legislation. These factors remain major risks in initiating geothermal schemes and they are particularly important as geothermal development is capital-intensive in its early stages. Currently a transmissivity of 20 Dm is considered to be necessary for economic development in the UK but this could be reduced by a change in the price of alternative fuels. In the immediate future the fact that there is no shortage of energy supplies together with the availability of cheap natural gas tends to militate against commercial development proposals. The first practical use of low enthalpy resources could be in Southampton if the City council does pursue the proposal to use the well drilled in 1981 to heat the Civic Centre and City Baths. However, the Southampton Well is situated near the eastern limit of the Triassic reservoir in the Wessex Basin, where conditions for development are marginal. A more convincing demonstration of the feasibility of developing low enthalpy resources for direct heating would be obtained from a scheme in the western part of the basin, where reservoir conditions are believed to be more favourable. A doublet at a coastal site would provide the necessary experience together with the opportunity to examine the feasibility of re-injecting water into the Triassic sandstones. This re-injection aspect is crucial to successful development as long-term development of a site will invariably require doublets to maintain the reservoir pressure, as well as dispose of the brine, and confidence in the re-injection process must be provided.

A principal conclusion arising from the assessment of the geothermal resources is that most of the low enthalpy energy is stored in the Triassic sandstones at 40 to 50 °C, particularly in east Yorkshire and Lincolnshire. These resources are at shallower, more accessible, depths and the Cleethorpes Well has indicated the high yields available. A practical scheme to develop these low temperature resources with heat pumps, and possibly incorporating several uses at the same site by cascading the resources consecutively to meet lower temperature requirements, would indicate the practicability of developing the resources for a variety of purposes.

Although the potential for using HDR resources is theoretically more widespread than is the case for low enthalpy resources, development at more than 200 °C at depths of less than 7 km is restricted principally to southwest and northern England. The greater potential exists at shallower depths; temperatures are about 100 °C at depths of less than 4 km below urban areas in, for example, the east Midlands, Hampshire and northern England. The use of these resources in urban areas for combined heat and power could be an attractive proposition. Contributions of electrical energy to the national grid from hot dry rocks are not so constrained by the geographical location of the site. If the technology of HDR systems can be developed successfully and proved to be economic, the long term HDR resources would be of greater significance than low enthalpy resources.

The investigation of the geothermal potential of the UK has reached the stage where it is necessary to demonstrate the feasibility of using this form of energy by carrying out field-trials in favourable areas that have been identified as a consequence of the extensive programme carried out over the last seven years.

This paper has reviewed a programme carried out by the British Geological Survey between 1977 and 1984 which was funded by the Commission of the European Communities and the Department of Energy of the UK. The authors acknowledge the contribution to the programme of many colleagues in the British Geological Survey and also in the Open University, the University of Bath, Imperial College, London, and Oxford University. The paper is published with the permission of the Director, British Geological Survey (NERC).

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